ARID ZONE RESEARCH
RECHERCHES SUR LA ZONE ARIDE
INVESTIGACIONES SOBRE LA ZONA ÁRIDA

WIND AND SOLAR ENERGY

Proceedings of the New Delhi Symposium

ÉNERGIE SOLAIRE ET ÉOLIENNE

Actes du colloque de New Delhi

ENERGÍA SOLAR Y EÓLICA

Actas del coloquio celebrado en Nueva Delhi

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ARID ZONE RESEARCH — VII
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PROCEEDINGS OF THE NEW DELHI SYMPOSIUM

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ÉNERGIE SOLAIRE ET ÉOLIENNE
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ACTAS DEL COLOQUIO CELEBRADO EN NUEVA DELHI

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I. *Compte rendu des recherches effectuées sur l'hydrologie de la zone aride.*
II. *Proceedings of the Ankara Symposium on Arid Zone Hydrology.*
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FOREWORD

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A FORMER *French member of the Advisory Committee on Arid Zone Research, the late André Nizery, once said that Unesco's Arid Zone Programme would have abundantly justified itself if its only achievement were that of bringing together scientists working on arid zone problems. Arid zone research is not limited to a single subject, indeed there is hardly a scientific discipline that has not a contribution to make towards the solution of the multiple problems which the arid lands present, nor is there any scientist working in this field who can afford to neglect the ideas, methods and results of his colleagues who are dealing with other aspects.*

Consequently the Advisory Committee on Arid Zone Research has made the holding of an annual symposium one of its major activities since the launching of the programme in 1951; and, in selecting the persons to be invited to contribute communications at the symposia, efforts have always been made to include as wide a range of scientific disciplines as possible.

The holding in India of the symposium on wind and solar energy in the arid zone was appropriate for two reasons, one sentimental and the other practical. The arid zone programme originated from a proposal by the Indian delegation at the Third Session of the General Conference of Unesco in 1947, so that in holding a symposium in India, the programme was in a way returning to its home. Practically it was appropriate, because India has done remarkable pioneering work in the field of solar energy. The advisory committee therefore learnt with keen satisfaction at its sixth session in November 1953 that the Indian Government had invited the Director-General to hold the symposium on wind and solar energy in India in the autumn of the following year.

The advisory committe established the scientific programme for the meeting, and the Indian Government nominated the National Institute of Sciences of India as the body responsible for all the arrangements in India. An organizing committee, under the chairmanship of Dr. K. S. Krishnan, F.R.S., was set up to carry out the heavy tasks involved. In accordance with the usual practice, the Indian Government invited participants from India and the countries of Asia, and Unesco invited those from other parts of the world. The symposium was also attended by representatives of the United Nations and those of its Specialized Agencies having arid zone interests, of the international scientific and technical organizations, and of Indian organizations working in this field.

The symposium was held from 22 to 25 October 1954 in the library of the National Physical Laboratory of India in New Delhi. Dr. Krishnan was elected chairman, Professor M. S. Thacker, vice-chairman for the section on wind energy, and Dr. H. Masson, vice-chairman for that on solar energy.

After the technical sessions were over, the Indian Government took the foreign participants on a study tour of the states of Rajasthan and Saurashtra by special plane. This opportunity to see the problems of typical arid and semi-arid lands in India was most valuable and greatly appreciated.

A session of the Advisory Committee on Arid Zone Research was held in conjunction with the symposium, in New Delhi from 19 to 21 October and at Bombay, after the study tour, on 2 November 1954. This arrangement was made to enable the committee to formulate recommendations to the Director-General on matters arising from the symposium. Two recommendations were made covering the points which most clearly emerged. The first concerned the evident need for more data. There is plenty of information about sunshine duration, but little about the energy received in those places where the duration indicates that useful amounts of solar radiation may be available. The committee consequently recommended that the Director-General endeavour to stimulate the collection of solar energy data, and that to that end he should convoke, in consultation with the World Meteorological Organization, a meeting of experts to establish a design for a simple standard pyrheliometer, suitable for general adoption in measuring solar energy.

The second recommendation came directly from the paper by Messrs. Golding and Thacker. The proposal made by the authors, of an assessment of the energy requirements of a small semi-arid zone community and the possibility of satisfying them by an integration of wind, solar and waste vegetable matter as sources, attracted considerable attention during the symposium. The committee recommended that Unesco take steps to encourage one or more Member States to undertake such a pilot project—calling, if necessary, for aid from the Expanded Programme of Technical Assistance.

Action in implementation of these recommendations is being taken by Unesco.

This volume contains the papers presented at the symposium, in their original language, either English or French, with a summary in the other language and in Spanish together with some account of the discussions.

The thanks of Unesco and its Advisory Committee on Arid Zone Research are due to the Indian Government for its invitation and for the efficient and comprehensive arrangements made, to the National Institute of Sciences and its president, Dr. K. S. Krishnan, to the late Dr. S. S. Bhatnagar, Director of the Indian Department of Scientific and Industrial Research, who was Chairman of the reception committee, to Professor M. S. Thacker, on whom as Indian member of the advisory committee a very heavy burden inevitably fell, to the National Physical Laboratory, which lent its rooms for the meetings, and finally to all the participants, from India and from abroad, who contributed by reading papers or taking part in discussions.

AVANT-PROPOS

Un ancien membre français du Comité consultatif de recherches sur la zone aride, le regretté André Nizery, a dit un jour que, même si le programme de la zone aride ne servait qu'à rapprocher les hommes de science qui s'occupent de ces problèmes, il aurait amplement sa raison d'être. En effet, les recherches relatives à la zone aride ne portent pas sur une seule catégorie de sujets ; on peut même dire qu'il n'est guère de disciplines scientifiques qui n'aient un rôle à jouer dans la solution des multiples problèmes que posent les terres arides, et aucun des savants travaillant dans ce domaine ne peut se permettre d'ignorer les idées, les méthodes et les conclusions de ceux de ses collègues qui étudient d'autres aspects de la question.

C'est pourquoi, depuis 1951, date de la mise en application de ce programme, l'organisation d'un colloque annuel constitue l'une des principales activités du Comité consultatif de recherches sur la zone aride ; et, en choisissant des communications présentées à ces colloques, le comité s'est toujours efforcé de faire appel à des représentants d'une gamme aussi large que possible de disciplines scientifiques.

Il était tout indiqué que le colloque sur l'énergie éolienne et solaire dans la zone aride se tînt en Inde, et cela pour deux raisons : l'une d'ordre affectif, l'autre d'ordre pratique. C'est en effet une proposition présentée par la délégation de l'Inde à la troisième session de la Conférence générale de l'Unesco en 1947 qui est à l'origine de ce programme, si bien qu'organiser un colloque en Inde c'était, en quelque sorte, faire un pèlerinage aux sources. D'autre part, les savants indiens ont fait œuvre de pionnier et accompli des travaux remarquables dans le domaine de l'énergie solaire. Aussi lorsque le comité apprit, lors de sa sixième session en novembre 1953, que le gouvernement indien avait invité le Directeur général à organiser le colloque sur l'énergie éolienne et solaire en Inde, à l'automne de l'année suivante, cette nouvelle suscita une vive satisfaction.

Le Comité consultatif établit le programme scientifique de la réunion et le gouvernement indien confia à l'Institut national des sciences le soin de prendre sur place toutes les dispositions voulues. Un comité d'organisation présidé par M. K. S. Krishnan, F.R.S., fut constitué pour s'acquitter de cette lourde tâche. Selon la coutume, les invitations furent adressées par le gouvernement indien aux savants de l'Inde et des autres pays d'Asie et par l'Unesco aux personnes originaires des autres parties du monde. Ont également assisté au colloque des représentants de l'Organisation des Nations Unies, de celles de ses institutions spécialisées qui s'occupent de la zone aride, des organisations internationales scientifiques et techniques et d'organisations indiennes compétentes.

Les séances ont eu lieu, du 22 au 24 octobre 1954, dans la bibliothèque du Laboratoire national de physique, à New Delhi. M. Krishnan fut élu président, le professeur M. S. Thacker, vice-président chargé de la section "énergie éolienne", et le D^r H. Masson, vice-président pour la section "énergie solaire".

Après la fin des travaux, le gouvernement indien mit un avion spécial à la disposition des participants étrangers pour leur permettre de faire un voyage d'études dans les États du Rajasthan et de Saurashtra. Tous furent enchantés d'avoir ainsi la possibilité de voir comment les problèmes caractéristiques des régions arides et semi-arides se posent en Inde.

A l'occasion de ce colloque, le Comité consultatif de recherches sur la zone aride a siégé à New Delhi du 19 au 21 octobre, et à Bombay (à l'issue du voyage d'étude) le 2 novembre 1954, en vue d'adresser des recommandations au Directeur général de l'Unesco sur les principaux points mis en lumière au cours du colloque. Deux recommandations ont été formulées : la première concerne la nécessité manifeste de recueillir une documentation plus abondante. On possède en effet une masse de données sur la durée de l'ensoleillement, mais on sait peu de chose sur l'énergie reçue en des lieux où cette durée est telle que des quantités utilisables d'énergie solaire peuvent s'y trouver disponibles. Le comité a donc recommandé que le Directeur général prenne des mesures en vue de stimuler le rassemblement de données sur l'énergie solaire, et notamment *qu'il convoque, de concert avec l'Organisation météorologique mondiale, une réunion d'experts chargée d'établir le plan d'un pyro-héliomètre, d'un modèle simple et normalisé, dont l'emploi pourrait être généralisé pour l'évaluation de l'énergie solaire.*

La deuxième recommandation découle directement d'une communication fort remarquée de MM. Golding et Thacker : ceux-ci avaient proposé qu'on dresse l'inventaire des besoins énergétiques d'une petite collectivité située dans une région semi-aride, et qu'on recherche dans quelle mesure l'emploi combiné de l'énergie éolienne, de l'énergie solaire et des résidus végétaux permettrait d'y pourvoir. Le comité a recommandé que l'Unesco prenne les mesures nécessaires pour encourager un ou plusieurs pays à entreprendre une expérience pilote de ce genre en faisant appel, le cas échéant, aux ressources disponibles dans le cadre du programme élargi d'assistance technique.

L'Unesco s'occupe actuellement de donner suite à ces recommandations.

Le présent volume contient les communications présentées lors du colloque, dans la langue originale — c'est-à-dire en anglais ou en français — mais accompagnées d'un résumé dans l'autre langue, et en espagnol, ainsi que de brefs comptes rendus des débats.

L'Unesco et le Comité consultatif de recherches sur la zone aride tiennent à exprimer leur gratitude au gouvernement indien, qui a bien voulu accueillir la réunion et n'a rien négligé pour en assurer le succès, à l'Institut national des sciences et à son président, M. K. S. Krishnan, au regretté M. S. S. Bhatnagar, directeur du Département indien de la recherche scientifique et industrielle et président du Comité de réception, au professeur M. S. Thacker, qui, en qualité de membre indien du Comité consultatif, a assumé une tâche très lourde, au Laboratoire national de physique où ont eu lieu les séances, et enfin à tous les participants, indiens et autres, qui ont présenté des communications ou sont intervenus dans les débats.

PREFACIO

El difunto André Nizery, que representaba a Francia en el Comité Consultivo de Investigación sobre la Zona Árida, dijo en una ocasión que el programa de la Unesco sobre la zona árida quedaba ampliamente justificado aunque sólo fuera por haber puesto en relación a los hombres de ciencia que estudian los problemas de las zonas áridas. Las investigaciones sobre esas regiones no se limitan sólo a un tema, ya que es difícil encontrar una disciplina científica que no pueda contribuir a la solución de los múltiples problemas que plantea; por lo tanto, ningún hombre de ciencia que trabaje en esa esfera puede desinteresarse de las ideas, métodos y resultados de sus colegas que se ocupan de otros aspectos de la misma cuestión.

Por consiguiente, el Comité Consultivo de Investigación sobre la Zona Árida ha hecho de la celebración de un coloquio anual una de sus actividades más importantes desde que se inició el programa en 1951; al seleccionar a las personas que deben ser invitadas a enviar comunicaciones al coloquio, se ha tratado en todo momento de incluir entre ellas a representantes del mayor número posible de disciplinas científicas.

El hecho de haber escogido la India para celebrar el coloquio sobre la energía eólica y solar en la zona árida se debió a dos razones: una sentimental y la otra práctica. El programa sobre la zona árida tuvo su origen en una propuesta presentada por la delegación de la India en la tercera reunión de la Conferencia General de la Unesco, en 1947, de manera que al celebrar el coloquio en la India el programa volvía, en cierto modo, a su lugar de origen. Desde el punto de vista práctico era además una elección apropiada, porque la India ha realizado importantes trabajos experimentales en la esfera de la energía solar. Por consiguiente, el Comité Consultivo, en su sexta reunión celebrada en noviembre de 1953, recibió con vivo agrado la noticia de que el gobierno de la India había invitado al Director General a celebrar en su país, en el otoño del siguiente año, el coloquio sobre la energía solar y eólica.

El Comité Consultivo preparó el programa científico de la reunión, y el gobierno de la India designó al Instituto Nacional de Ciencias de la India para que se encargara de tomar todas las disposiciones necesarias para su organización. Se creó un comité organizador, presidido por el Dr. K. S. Krishnan, para llevar a cabo las arduas tareas que entrañaba la preparación. De acuerdo con las normas usuales, el gobierno indio invitó para participar en dicho coloquio a hombres de ciencia de la India y países asiáticos, y la Unesco invitó a los de otras regiones del mundo. También asistieron al coloquio representantes de las Naciones Unidas y de los organismos especializados que se interesan por los problemas de la zona árida, de las organizaciones científicas y técnicas internacionales, y de las organizaciones indias que trabajan en esa esfera.

El coloquio se celebró del 22 al 25 de octubre de 1954 en la biblioteca del Laboratorio Nacional de Física de la India, de Nueva Delhi. Fué elegido presidente el Dr. Krishnan, y vicepresidentes el profesor S. Thacker, para la sección de la energía eólica, y el Dr. H. Masson, para la de la energía solar.

Una vez terminadas las sesiones técnicas, el gobierno indio organizó para los participantes extranjeros un viaje de estudios por los Estados de Rajasthan y Saurashtra, en un avión fletado especialmente con ese fin. Esa oportunidad de entrar en contacto directo con los problemas de las zonas áridas y semiáridas características de la India fué sumamente apreciada y provechosamente utilizada.

En relación con el coloquio, el Comité Consultivo de Investigación sobre la Zona Árida celebró una reunión en Nueva Delhi del 19 al 21 de octubre y en Bombay el 2 de noviembre de 1954, después del viaje de estudios. Se tomó tal disposición para que el Comité pudiera formular recomendaciones al Director General sobre cuestiones suscitadas por el coloquio, resultando de ello dos recomendaciones que comprendían los puntos más importantes. La primera se refería a la necesidad cada vez más evidente de conseguir una información más completa. Se poseen muchos datos sobre el tiempo de insolación pero pocos sobre la energía recibida en aquellos lugares donde el tiempo de insolación indica que podrían *obtenerse cantidades útiles de radiación solar. Por consiguiente, el Comité recomendó que el Director General trate de estimular la compilación de datos sobre la energía solar, y que, para ese fin, debería convocar, previa consulta con la Organización Meteorológica Mundial, una reunión de expertos que estudiasen un modelo normalizado de piroheliómetro sencillo que pueda adoptarse para medir la energía solar.*

La segunda recomendación tuvo su origen directo en un estudio presentado por Golding y Thacker. En él, los autores proponen que se realice un cálculo de las necesidades energéticas de una pequeña comunidad en una zona semiárida y se estudie la posibilidad de satisfacerlas mediante la conjunta utilización de la energía eólica, solar y de los desperdicios vegetales, lo cual atrajo considerable atención durante el coloquio. El Comité recomendó que la Unesco tomara las disposiciones necesarias para fomentar la realización en uno o más Estados Miembros de un proyecto experimental de ese tipo, solicitando ayuda, si es preciso, del Programa Ampliado de Asistencia Técnica.

La Unesco ha adoptado las medidas necesarias para la aplicación práctica de esas recomendaciones.

Este volumen contiene los documentos presentados en el coloquio, en una de las dos lenguas de trabajo (inglés o francés), con un resumen en la otra lengua y en español, junto con unas notas sobre los debates.

La Unesco y su Comité Consultivo de Investigación sobre la Zona Árida agradecen al gobierno de la India la invitación y las eficaces disposiciones tomadas para la celebración del coloquio, al Instituto Nacional de Ciencias y a su presidente el Dr. K. S. Krishnan; al difunto Dr. S. S. Bhatnagar, director del Departamento Indio de Investigaciones Científicas e Industriales, que fué presidente del Comité de Recepción; al profesor S. Thacker, sobre quien recayó necesariamente una pesada tarea en su calidad de miembro indio del Comité Consultivo; al Laboratorio Nacional de Física, que prestó sus locales para las reuniones, y por último a todos los participantes, de la India y del extranjero, que contribuyeron al coloquio mediante la lectura de comunicaciones o tomando parte en los debates.

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INAUGURAL ADDRESS

by

SHRI KESHAVA DEVA MALAVIYA

Deputy Minister
for Natural Resources and Scientific Research

I HAVE great pleasure in formally inaugurating, and in associating myself with, this International Symposium on Wind and Solar Energy in the Arid Zone. It was indeed very good of the advisory committee of Unesco to have accepted the offer of India to co-sponsor this symposium. Our countrymen will be thankful for this opportunity of discussing the problems of the arid zones, with a view to discovering the solutions for some of the most difficult problems with which nature has presented us. I am sure that our scientists will benefit immensely by these international discussions. The lessons and experiences here gained can then be translated effectively into action, and save us from many national anxieties.

Cheap power is the cry of the day. Coal, oil and waterfall have changed the entire picture of the world. But, as is known, the world reserves of oil and coal are definitely limited: it is thought that they may all be exhausted in a very few centuries even if they are consumed at no more than the present rate. Even if we succeed further in harnessing all the radio-active energy which can be made available to us, from uranium or thorium or like elements at a colossal cost and through complicated processes, it too may not last for more than a few more centuries after exhausting the coal, oil and waterfall resources of the world. As we go on probing the mysteries of nature, and thereby advance our knowledge, we come to the grim realization that after consuming the entire reserves of coal and oil and radio-active minerals we shall, in a few centuries, have no source of energy left for generating power. And so life on our globe would come to an end, unless another source of energy, more bountiful in nature and obtainable in an easier form, is made available to humanity. When I view the activities of the scientists working under the auspices of Unesco in this context the importance of a symposium of this nature becomes both more thrilling and more important. More objectively speaking, the utility of such a symposium is particularly great for India, since a large part of India has arid and semi-arid conditions. The practical and economic utility of wind power and the rays of the sun will conserve the plant and animal material available to us, at present being consumed very rapidly for fuel purposes.

Since the discovery of electricity the relation of man to his environment has radically changed, and our standards of comfort have been enormously raised. This discovery has had an unfortunate aspect too. It has created a bigger gap between the peoples of the world, since the nations that invented tools to generate electricity with the help of coal, oil and waterfall improved their national life by leaps and bounds, leaving countries like ours and others in Asia, Africa and elsewhere from every point of view far behind. A comfortable house or a decent income or a well-built town—all depend on the availability of cheap power—as much as the building up of a strong navy, army or air power. This gap in the standards of living and the material strength of nations seems to have been caused directly by the fact that some nations could not take advantage of these natural assets and had no knowledge how to generate electricity for their use, while others had the necessary knowledge and possessed the facilities to utilize it. We are thus faced by two great problems: (a) an overall diminishing reserve of sources of power in the whole of the world; and (b) an inequitable distribution of the necessary knowledge which enables the whole world to move forward to live peacefully and prosperously.

It is a source of great pleasure to all of us that such symposia as the present one are seeking to solve both these problems. The scientists and the engineers meeting here will consider how best to utilize the motion of wind and the rays falling from the sun, so as to supplement on a enormous scale the energy that we derive today from coal or oil or waterfall. And not only should we derive energy from wind and sun but we should aim at getting it cheaply. Our scientists today aim, therefore, at economy and simplicity in the processes of exploitation of wind velocity and solar energy.

It is equally a happy feature that the scientists of different countries are invited to join in these symposia. What one country knows will thus be shared by all, each will be glad to help the other in translating theoretical discoveries into practical knowledge. That this mutual communication of knowledge is international and purposeful is of great promise for all mankind.

Are we anyway near discovering simple and cheap processes of exploitation of these limitless natural resources? I can only share the optimism of many of you. Slowly but surely we are nearing our objectives, whether it is a solar cooker, a solar battery, a windmill or a hoard of small achievements in this direction, they are all contributing steadily to the discovery of facts which will one day lead us to solutions. Scientists have succeeded in the past, wholly or partly, in unravelling many natural and mysterious processes that were beyond us. Why should we then assume that the mysterious process by which the sun's rays create life and food in plant and animal should remain a mystery to us? Whether it is man or plant or animal—all are competing amongst themselves and living because of the sun's energy. The wind also makes its contribution. The mysterious processes by which all this is going on have to be elucidated for the good of mankind. The sooner we do it, the nearer shall we be towards peace, happiness and universal equality and brotherhood.

DISCOURS D'OUVERTURE

de

SHRÍ KESHAVA DEVA MALAVIYA

Sous-secrétaire d'Etat
aux ressources naturelles et à la recherche scientifique

J'AI le grand plaisir de déclarer officiellement ouverts les travaux de ce colloque international sur l'énergie éolienne et solaire dans la zone aride, auxquels je tiens à m'associer personnellement. Je remercie le Comité consultatif de l'Unesco d'avoir bien voulu accepter l'offre de mon pays et patronner ce colloque. Nos compatriotes lui sauront gré de leur fournir l'occasion de prendre part à des échanges de vues sur ces problèmes des régions arides, qui comptent parmi les plus ardus que la nature ait posés à l'homme, et de travailler à les résoudre. Je suis convaincu que nos savants tireront un immense profit de ces débats internationaux. Grâce aux leçons et aux enseignements qu'ils en retireront, ils pourront dissiper bon nombre des inquiétudes qu'éprouve notre pays.

Se procurer de l'énergie à bon marché, tel est aujourd'hui l'objet de tous les désirs. Le charbon, le pétrole et l'énergie hydro-électrique ont transformé le monde de fond en comble. Mais, comme chacun le sait, les réserves de pétrole et de charbon sont loin d'être illimitées et l'on estime qu'elles seront totalement épuisées dans un très petit nombre de siècles, à supposer même que le rythme de leur exploitation ne s'accélère pas. Et si nous réussissons à tirer parti de toute l'énergie radio-active que l'uranium, le thorium ou d'autres corps analogues peuvent nous fournir, à un prix de revient colossal et après des opérations très complexes, peut-être ne réussirons-nous qu'à repousser l'échéance de quelques siècles. A mesure que nous pénétrons plus avant dans la connaissance des mystères de la nature, une cruelle vérité s'impose peu à peu à notre esprit : dans quelques siècles, après avoir épuisé la totalité des gisements de charbon, de pétrole et même de minerais radio-actifs, nous n'aurons plus rien dont nous puissions tirer de l'énergie. Alors la vie disparaîtra de la planète à moins qu'une autre source d'énergie, plus féconde et plus aisément accessible, ne soit découverte. Lorsque j'envisage sous cet angle l'activité des hommes de science qui travaillent sous l'égide de l'Unesco, l'importance capitale de la présente réunion m'apparaît de façon plus frappante encore. D'un point de vue plus limité, ce colloque offre une utilité particulière pour l'Inde, puisqu'une grande partie du territoire de ce pays est aride ou semi-aride. L'exploitation de l'énergie éolienne et du rayonnement solaire, si elle est assurée par des moyens pratiques et économiques, nous permettra de ménager les réserves d'énergie végétale et animale que nous consommons actuellement à un rythme très rapide.

Depuis la découverte de l'électricité, les rapports de l'homme avec son milieu se sont radicalement transformés et sa vie matérielle est devenue infiniment plus facile. Mais cette découverte a eu aussi des conséquences moins heureuses : elle a élargi la brèche entre les différents peuples du monde, car les nations qui ont inventé les moyens de produire de l'électricité à partir du charbon, du pétrole ou de l'énergie hydraulique ont amélioré très rapidement leurs conditions d'existence et laissé loin derrière elles, à tous égards, de nombreux pays d'Asie, d'Afrique et d'autres parties du monde, le nôtre en particulier. Maisons confortables, revenus suffisants, villes bien construites — pour avoir tout cela il faut disposer d'énergie à bon marché, tout comme pour se donner une marine, une armée et une aviation puissantes. Ces différences de niveau de vie et de force matérielle entre nations semblent être la conséquence directe de l'incapacité des unes à tirer parti de leurs atouts naturels et à produire l'électricité dont elles avaient besoin, face aux connaissances et à l'équipement des autres. Nous nous trouvons donc en présence de deux grands problèmes : d'une part l'ensemble des réserves énergétiques mondiales diminue, de l'autre les connaissances qui permettraient à tous les peuples de s'acheminer vers la paix et la prospérité sont inégalement partagées. C'est pour nous un puissant réconfort qu'une réunion comme celle-ci ait pour objet de résoudre ces deux problèmes. Les savants et les ingénieurs ici rassemblés rechercheront le meilleur moyen d'exploiter la force des vents et le rayonnement du soleil afin d'ajouter des quantités immenses d'énergie à celles que nous tirons aujourd'hui du charbon, du pétrole ou des chutes d'eau. Mais il nous faut chercher non seulement à capter l'énergie du vent et du soleil, mais aussi à l'obtenir à bon compte. C'est pourquoi nos savants se préoccupent aujourd'hui de mettre au point des procédés économiques et simples d'exploitation.

Il est aussi de bon augure que des hommes de science de différents pays soient invités à prendre part à de telles réunions. Le savoir de chaque nation sera ainsi partagé entre toutes, et chacune sera heureuse de voir transcrire dans la pratique ses propres découvertes théoriques. Internationaux et librement consentis, ces échanges intellectuels ouvrent de vastes espérances à l'humanité tout entière.

Sommes-nous donc près de découvrir des moyens simples et peu coûteux d'exploiter ces inépuisables ressources naturelles? Je ne puis, à cet égard, que partager l'optimisme de beaucoup d'entre vous. Lentement, mais sûrement, nous approchons du but. Le four solaire, la pile photo-électrique, l'éolienne, une foule de réalisations de moindre envergure sont autant de contributions à la mise au point des solutions définitives. Des savants ont déjà réussi à percer, plus ou moins, bien des mystères de la nature. Pourquoi donc le mystérieux processus grâce auquel le rayonnement solaire crée et entretient la vie végétale et animale demeurerait-il impénétrable? Homme, plante ou animal, toutes les créatures engagées dans la lutte pour la vie subsistent uniquement grâce à cette énergie. Le vent, lui aussi, est une force puissante dont nous devrions pouvoir tirer parti. Ces mystérieux mécanismes doivent être élucidés le plus tôt possible pour le bien de l'humanité, afin que s'ouvre bientôt l'ère de la paix, de la prospérité, de l'égalité et de la fraternité universelles.

DISCURSO INAUGURAL

por

SHRI KESHAVA DEVA MALAVIYA

Subsecretario de Recursos Naturales e Investigaciones Científicas

Constituye para mí un gran placer inaugurar este coloquio internacional sobre la energía solar y eólica en la zona árida, y asociarme así personalmente a sus tareas. En realidad fué un gran acierto que el Comité Consultivo de la Unesco aceptara el ofrecimiento de la India de patrocinar este coloquio. Nuestros compatriotas estarán siempre agradecidos por la oportunidad que así se les ofrece de examinar los problemas de la zona árida, con miras a encontrar solución a algunos de los problemas más arduos que la naturaleza nos plantea. Tengo la seguridad de que nuestros científicos se beneficiarán inmensamente en este debate internacional. Las lecciones y experiencia que se logren aquí podrán ser eficazmente traducidas en actividades prácticas que nos eviten ulteriormente muchas preocupaciones nacionales.

"Energía barata" es el grito del día. La utilización del carbón, el petróleo y los recursos hidráulicos ha cambiado totalmente la faz de la tierra. Pero como todos sabemos, las reservas mundiales de petróleo y de carbón son limitadas: se calcula que podrán quedar agotadas dentro de unos siglos, aunque no aumente el ritmo actual de consumo. Aun si logramos utilizar en mayor escala toda la energía radioactiva que podemos obtener del uranio, del torio o de elementos análogos —a un precio colosal y por medio de complicados procedimientos— no pueden durar tampoco más que algunos centenares de años, una vez agotado el carbón, el petróleo y los recursos hidráulicos de la tierra. Al ir descubriendo los misterios de la naturaleza y aumentando nuestros conocimientos llegamos a la terrible conclusión de que después de consumir todas las reservas de carbón, petróleo y minerales radioactivos, dentro de unos cuantos siglos no dispondremos ya de más fuentes de energía. De este modo, la vida en nuestro planeta tocará a su fin, a menos que se descubra en la naturaleza otra fuente de energía más abundante y de más fácil obtención. Cuando considero las actividades de los hombres de ciencia que trabajan en esa esfera bajo los auspicios de la Unesco, la importancia de un coloquio de esa índole se me aparece mucho más considerable. Hablando más objetivamente, la utilidad de un coloquio de ese tipo es muy grande para la India, ya que una parte considerable del país está constituída por regiones áridas y semiáridas. La utilización práctica y económica de la energía eólica y de los rayos solares servirá para conservar las reservas de energía vegetal y animal que se consumen actualmente a un ritmo muy acelerado.

Desde el descubrimiento de la electricidad, la relación del hombre con el medio ha cambiado radicalmente, mejorando también de manera no menos radical nuestro nivel de vida. Sin embargo, ese descubrimiento ha tenido asimismo un aspecto desfavorable: ha aumentado la diferencia que existe entre los distintos pueblos, del mundo, ya que las naciones que han inventado aparatos para generar electridad por medio del carbón, el petróleo y los recursos hidráulicos mejoraron su nivel de vida a pasos agigantados, dejando muy atrás desde todos los puntos de vista a países como el nuestro y otros de Asia, África y de diversas regiones. Una casa confortable, un ingreso económico adecuado o una ciudad bien construída, todo ello depende de poder disponer de energía a un precio económico, lo mismo que la formación de una marina o de un ejército de tierra o del aire poderosos. Esa diferencia en el nivel de vida y la fuerza material de las naciones parece haber tenido su origen directo en el hecho de que algunas naciones no han podido beneficiarse de esas posibilidades naturales y no han sabido producir electricidad, mientras otras poseían todos los conocimientos y contaban con los servicios necesarios para utilizar tal fuente de energía. Por consiguiente nos encontramos ante dos problemas: una disminución general de las reservas de fuentes de energía en todo el mundo; una distribución desigual de los conocimientos necesarios que permiten al mundo entero un progreso pacífico y próspero. Es para todos nosotros muy alentador observar que un gran coloquio como el presente se esfuerza por hallar la manera de resolver ambos problemas. Los hombres de ciencia y los ingenieros aquí reunidos estudiarán los mejores procedimientos para utilizar la fuerza del viento y la energía solar, de modo que vengan a sumarse en una escala enorme a las energías que hoy obtenemos del carbón, del petróleo o de la fuerza hidráulica. Y no sólo se trata de obtener energía del viento y del sol sino de obtenerla económicamente. Actualmente, nuestros científicos se esfuerzan por descubrir procedimientos económicos y sencillos para explotar la energía eólica y solar.

También es de buen augurio el que se haya invitado a hombres de ciencia de diferentes países para participar en esos coloquios. De este modo, los conocimientos de un país serán compartidos por todos y todos sentirán la satisfacción que nace de la mutua ayuda por traducir los descubrimientos teóricos en conocimientos prácticos. Esa comunicación del conocimiento a todos los países y con un fin determinado constituye una gran promesa para la humanidad entera.

¿Está ya cerca el día en que hayamos de descubrir procedimientos económicos para la explotación de esos ilimitados recursos naturales? Yo comparto el optimismo de muchos de los aquí presentes. Despacio, pero de manera segura, vamos acercándonos a nuestros objetivos. Ya sea una cocina o una batería solares, un molino de viento o una multitud de pequeños logros en ese sentido, todos ellos contribuyen firmemente al descubrimiento de datos que algún día permitan encontrar soluciones. En el pasado, los hombres de ciencia lograron atravesar total o parcialmente el velo del misterio que cubría a muchos procesos naturales. ¿Por qué suponer, pues, que el misterioso proceso por el cual los rayos del sol crean la vida y las substancias nutritivas en las plantas y en los animales deba seguir siendo siempre un arcano para nosotros? El hombre, como todo animal y vegetal, lucha por la existencia y existe gracias a la energía solar. El viento también aporta su contribución a la vida. Todos los procesos hoy envueltos en el misterio, que son la base misma de la vida, deben ser desentrañados para el bien de la humanidad. Cuanto antes lo consigamos, más pronto nos acercaremos al reino de la paz, el bienestar, la igualdad y la fraternidad universales.

I

WIND ENERGY
ÉNERGIE ÉOLIENNE
ENERGÍA EÓLICA

GENERAL REVIEW PAPER

by

Professor D. **Dresden** (Netherlands)

Expert opinions differ widely on the question: "For how many more years can fossil fuels supply us with an adequate amount of heat and energy?" These differences of opinion are only too natural, for the problem under consideration deals with a number of insufficiently defined concepts such as: "adequate", "us," "can". We can none of us prophesy how the size of populations will change in such countries as are (or may become) interested in heat and energy, so we do not know for what number of human beings the "us" stands. We can as little foresee what, in a number of years from now, will be considered as an "adequate" supply of heat and energy per capita. And as for the "can", this depends upon the price (in money or in labour or in sacrifice) one is prepared to pay for a unit of heat or energy in the form of a ton of coal or oil.

On the other hand none of the experts denies that there will be *some* time when mankind will have to do without fossil fuels. And this unanimity again is only too natural, because it is a fact that in using these fuels we are living on *capital* and not on *income.* The capital may be bigger or smaller than we believe it to be; we may adapt our spending to its size, but one day it will have been exhausted.

Conditions are considerably different in the field of hydropower. Here we use a source which is due to solar energy of recent date, perhaps as recent as a few days ago (hydropower derived from rain-rivers); perhaps as long ago as a number of years (when it is derived from glacier-rivers, for which the original energy consisted in the evaporation of the water which was subsequently deposited at the top of the mountain).

So we need not be afraid of running out of this source of energy but—in contradistinction to coal and oil—it cannot as a source be transported to places where it is more desirable than where it is found.

The outlook for atomic energy seems to be favourable, although many problems are still awaiting solution. The ease of transportation of this source, owing to its extremely concentrated form, though it may be somewhat impaired by the necessity of protective containers, is many times superior to that of coal and oil. The quantities of fissionable material seem to be far in excess of the most optimistic estimates for coal and oil, but still, *in principle*, its use again means living on capital. However, in this case the capital is so big that one can only hope for a satisfactory solution of the many practical problems. There is still another form of solar energy, which may undoubtedly be considered as income—wind energy, which is due to very recent heating of the atmosphere by the sun. This highly attractive feature of being independent of capital is accompanied by the serious drawback that the income is very irregular in most parts of the world, especially where fairly strong winds (a high rate of income) blow at intervals; the far more regular trade winds are relatively weak. There is, however, no possibility of transporting this *source* of energy; of course *products* made by using it and possibly embodying energy in some other form can be transported, as can hydropower.

The question has long been discussed, whether in our times much further development of wind power might be expected, due account having been taken of the situation in the other fields of power supply as roughly sketched above. It was clear that two separate questions had to be dealt with: (a) Application for small power in places where the only alternative source would have been some small prime mover such as a diesel or gasoline motor; in these cases wind power, once selected, would have to be relied upon as the only available source. (b) Application for as large power as would prove to be practical, with, as its main purpose, the conservation of fossil fuels during the time the wind would blow with enough force.

These two fields of application being different in nearly every respect, the general question, "Whether in our times much further development of wind power might be expected?" may well be viewed very differently in the two separate fields.

When, in April 1950, an international wind power group had been formed, it soon became clear to its members that much work would be required to investigate the possibilities in both fields. Quoting from the foreword of the collection of technical papers recently published by the group as its final report,[1] the following passages may be of interest:

> The technical papers submitted indicate that considerable progress has been made by the wind power group in assessing the technical aspects of wind power and there is ample evidence that reputable manufacturers are now building wind power generators of progressive designs. It is believed that this collection of technical data is unique and should be of considerable value to any national organization or private manufacturer contemplating wind power development.

RESULTS ACHIEVED BY WIND POWER GROUP OF OEEC

INTERNATIONAL COLLABORATION

Perhaps one of the most important results of the formation of the wind power group has been to bring together experts from many countries who have a real and practical interest in the development of wind power, and who, prior to the formation of this group, had no international organization through which they could collaborate. It became obvious at the initial meetings of the group that much could be achieved by the free exchange of information and by co-operative research. There has been a considerable exchange of technical information, not only through OEEC channels but also directly between the member countries. As a result of this collaboration the utilization of wind power is being seriously considered in many countries by national governments.

CO-OPERATIVE RESEARCH

Wind power research, in its earlier stages, involves experimental determination of wind regimes at especially windy sites and detailed study of wind behaviour under different climatic conditions. Design and costing studies are needed to decide the relative economy of various types of wind-driven plant and to compare them with other forms of power plant. These studies must be followed by tests of comparatively small pilot plants under different operating conditions prior to the construction of larger prototypes.

It is most important that wind velocity measurements and records should be made with some degree of standardization so that intercomparison is facilitated and the data collected can be used directly by designers.

The existing state of technical knowledge did not justify the construction of large wind-driven plant by co-operative effort as a first step. Much preliminary work is necessary to indicate the form which such a plant should take. Hence the co-operative research started under OEEC auspices was concerned mainly with wind surveys, methods of wind measurement and design and costing studies.

WIND REGIME STUDIES

For the reasons explained in the preceding paragraph the work of the wind power group to date has been mostly concerned with the study of methods of measuring wind regimes, collecting operating data on existing wind power generators and with the economics of wind power. There was very little published up-to-date data on the desirable topographical features for a wind power site, or on methods of estimating the annual energy production by a wind-driven generator erected on a given site. A considerable amount of theoretical work, backed by field work to verify theoretical calculations, has been carried out in the United Kingdom, France and Denmark, and reports on this work are included in this volume of technical papers. The close agreement between theory and practical experience, mainly in Denmark, has encouraged the group to state that there is now sufficient fundamental information available on which to base reasonably sound estimates of the wind power and annual energy available at any given site, and also that the essential requirements for a suitable site have now been determined.

Difficulties in correlating the results of wind regime studies made in different countries with different types of measuring instruments led to a recommendation by the group that some effort should be devoted to the standardization of meteorological measurements for wind power purposes, of instruments, of wind speed classification and of methods of presenting and analysing the results of measurements.

The exchange of measuring instruments between member countries was recommended and some exchanges have already been made so that the interpretation of the results of wind studies is now on a fairly sound basis.

ECONOMICS OF WIND POWER

It is generally agreed by all the expert members of the group that the development of wind power, under proper conditions could be an important factor in the economic life of some countries, and sufficient scientific and technical information has been produced to provide a basis for a sound estimate to be made of its possible economic contribution.

It has been established, from the detailed wind speed surveys made in the United Kingdom, France and Denmark, that there is a much larger supply of energy available in the wind than is generally imagined by engineers who have not made a close study of the subject. A number of technical papers on this aspect of the group's work are included in this volume.

LARGE-SCALE DEVELOPMENTS

Successful wind-driven generators of capacity up to 70 kw., are now operating in Denmark. Of two installations of 100 kw. each in the United Kingdom embodying new technical features suggested by recent aeronautical research, one is under test at its final site in the Orkney Islands and the other, of a different design, is being erected for initial trials at a testing site at St. Albans, Herts. The largest plants in Denmark have already provided some extremely valuable operating experience and are reported on in this volume.

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[1] *Wind Power*. Technical papers presented to the Wind Power Working Party of OEEC. Containing 44 original papers from 10 countries, available from TNO, The Hague, Konigskade 12, against payment of fl.12.50 plus freight.

The group has discussed large-scale developments using wind-driven machines with individual capacities of the order of 3,000 kw., but it will take several years of research and development before units of this size can be put into production in quantity. Study of the information published in the United Kingdom decidedly points to a possibility of the production of electrical energy from wind power able to compete with that from steam plants. It has also been found in the United Kingdom that many sites exist where large scale developments could be made and the output fed into the National Grid System.

The existence of research stations which could provide facilities for fundamental and applied research in the subject has been made generally known and they are listed in Technical Paper No. 42.

There have been frequent visits by some members of the group to examine and discuss developments in other countries and this fact is indicative of the interest which the group has aroused.

PREPARATION OF TECHNICAL PAPERS

One of the major efforts of the group was to initiate the preparation of technical papers by experts in various phases of wind power development both theoretical and practical. The papers submitted to the wind power group by these experts are published in this volume.

It may appear from the list of titles that there has been some duplication of effort and that some of the papers might have been combined and published under a joint authorship. The wind power group felt, however, that as these papers represented the author's original approach to the subject they should be reproduced independently.

BIBLIOGRAPHY OF WIND POWER

One of the recommendations made at the November 1950 meeting in London was the preparation of a bibliography relating to wind power. Both the French delegate, Monsieur Argand, and the United Kingdom delegate, Mr. Golding, have already prepared extensive bibliographies and the latter is co-ordinating the two. When this has been done, it is proposed to publish the combined bibliography as a supplement to this volume. This should then be the most up-to-date bibliography available on the subject of wind power.

GLOSSARY OF WIND POWER

A glossary has been started (Technical Paper No. 44) on French and English technical terms related to wind power. It is by no means complete and it is hoped that all authors will make further contributions for inclusion in the proposed supplement, Wind Power Bibliography.

In the first-mentioned field, the typical isolated-plant installation for small power, far more experience existed than in the second, the application for large power. Even apart from the ancient windmills[1] in many countries, of which several attractive representatives are still doing useful work, La Cour in Denmark, as early as 1890-96, did excellent research work in connexion with generating electricity by wind power.

At that time there was no reason to consider anything but D.C., which moreover possessed the attractive feature of making storage of energy in a battery possible and also practical for the small quantities of energy concerned. (It is interesting to note that one of the papers in the book mentioned above, contributed by Mr. J. Juul, department engineer of the South East Zealand Electricity Co. of Haslev, Denmark, deals with: "Conversion of Wind Power Plant from D.C. to A.C. Output." This refers to an installation developing up to 42 kw.)

During the years 1900-10 several hundred similar wind power plants of 3-30 kw. capacity were established in Denmark, supplying D.C. to the larger estates or to villages.

An interesting experiment utilizing an old Dutch windmill, combining its use for driving a pump with the generation of electricity, is reported in a paper contributed by the Netherlands Council for Applied Scientific Research. This was a case of A.C., the generator being connected to the public grid.

Only in recent years has attention been devoted to the possibility of developing much larger units for the conservation of fuel.[2] This necessitates profound studies of a technical (mechanical) nature as well as long-term measurements of available wind energy in various suitable sites. A number of papers are concerned with these subjects, among which may be mentioned contributions from England, France and Germany.

A technical problem of the first order in the design of these large-sized units arises from the fact that the number of revolutions of the propeller shaft is necessarily low, even though the design of the blades aims at a high "specific speed". The transmission between the propeller and the electric generator tends to become excessively heavy, as does the generator itself, unless suitable means are found to increase the speed of the shaft of the generator.

In England two plants of 100 kw. each have been erected, the results of which are not yet publicly available. They should be regarded as prototypes for units of 1,000 kw. or more in which class the Smith-Putnam experimental plant at Grandpa's Knob, Vermont, U.S.A. commanded much attention.[3]

For the smaller and medium powers (1-80 kw.) intended to produce electric current, it is in the first place a question of further perfecting automatic regulation, simplifying the electrical part of the installation without sacrificing reliability, and standardizing the parts so as to lower the cost of investment.

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[1] Not only in Holland and other Western European countries but probably those set up much earlier in Greece and in the neighbourhood of the frontier between Iran and Afghanistan.

[2] A fairly complete survey is given in *Windkraftwerke* by Hans Witte. R. A. Lang, 1950.

[3] P. C. Putnam. *Power from the Wind.* D. van Nostrand, 1948.

For the large units one of the first problems is the selection of suitable sites, where the total wind energy available through the years bears a favourable relation to the maximum momentary energy for which the machinery must be designed. As practically the whole of the cost of electrical energy generated by wind power is directly attributable to the cost of investment, it is of the utmost importance that for a certain amount invested the total yearly production of electrical energy should be as high as possible. Or, to view it strictly in connexion with the efforts to stretch the life of our fuel reserves, for a given investment the greatest possible quantity of fuel must be saved during the life of the installation.

For these large plants one need not think of a way to *store* a temporary surplus of energy as the quantities involved make this impracticable. In consequence, such plants will be effective only if they are connected to a grid of sufficient capacity and load to take all the energy generated by a favourable wind at any given time.

Investigators in France as well as in England and in Germany have given much attention to the development of methods to test the suitability of sites for large wind power units.

This work automatically promoted the development of suitable instruments for measuring and recording varying (and often very rapidly varying) wind speeds. In the Netherlands measurements have been going on for over a year to collect statistical data on the regime of the wind near the western coast.

From what has been published least progress appears to have been made in the design problems arising for large-power units. It is possible however, that manufacturers of this type of machinery have done important work in their experimental and development departments, the results of which have not yet been released. There is in fact, sound reason for this assumption and it will probably be only a few years before firm quotations can be had for complete installations, guaranteed to be reliable and for powers far in excess of the 100 kw. of the two prototypes now available in England.

Among the most important problems in design should be mentioned a provision to keep the installation in service under winds of a far higher velocity than the "normal" speed prevailing at a certain site. It would be doubly attractive if the efficiency under such winds could remain favourable, but a certain sacrifice in this respect would not do much harm. It should be possible, however, to leave the machinery without continuous attendance, relying on automatic devices to adapt the propeller blades etc. to extreme changes in wind force and even to strong gusts of wind.

In view of the fact that changes in the "fickle" wind can occur very rapidly, the required automatic regulations must have a very quick response.

Another factor of reliability is resistance of all parts against vibration. Not only does the wind itself frequently show strong pulsations which give rise to vibration in the elements of the machinery, but it is known from experience with aeroplanes, that even under a constant wind, parts may have a tendency to vibrate (flutter) and collapse under the strain.

Of course all parts exposed to atmospheric influences must be protected by design, material and finish against deterioration by rain, snow, sun, frost, etc. It will not prove an easy matter to create units which will give satisfaction in moderate climates with much rain, nor in extremely cold winters or under the fiery sun in some arid zones.

This last consideration points to the fact that we have here touched on practically no special point in connexion with the arid zone. It might even be asked whether there is any reason why our general conclusions should be modified for conditions prevailing in this zone. In fact, the validity of what has been discussed earlier, does not depend upon moisture or dryness of the atmosphere or the soil. It is another aspect of wind power which deserves special consideration for the arid zone. When the wind-driven propeller is used to drive an electric generator it is highly desirable to keep the number of revolutions of the propeller as nearly constant as possible, and in the case of A.C. (3-phase) in parallel with a grid, a practically constant speed is an absolute requirement.

The result is that in a period of stronger wind the extra power available can only be partly utilized, because a fuller use would be possible only by allowing the propeller to turn at a higher speed.

Without a detailed explanation of the action of the wind on the blades of a propeller,[1] it may be clear that the wind in passing through a moving propeller can never transmit *all* of its kinetic energy to the blades, for the air has to *leave* the plane of the propeller and this implies that it retains *some* speed. Now the percentage of its kinetic energy which is given off to the machinery depends upon many factors, one of these being the proportion between wind speed and blade speed. If the propeller has been designed to possess a maximum efficiency (meaning to absorb a maximum percentage of the kinetic energy of the air) under a certain speed of the air, this efficiency will drop under a different wind speed. This drop may be partly counteracted by means of changing the active profile of the blade (this is a task for a suitable regulating device) but it cannot be entirely avoided.

Now if the propeller does not drive an electric generator but a centrifugal pump, there is no reason why a higher speed of the shaft would not be *admissible* in periods of stronger wind. Supposing that the application of wind power in arid regions is particularly welcome for irrigation purposes, it appears that these sources of energy can be most economically designed so as to drive pumps without the intervention of electric machinery. During periods of stronger winds the pump will then be driven at a higher speed and discharge more water; it is true that under these circumstances the overall efficiency will be somewhat reduced but a considerably greater part of the extra available power in the wind will be utilized than in the case of a constant propeller speed.

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[1] This point may be further studied in a number of papers in the collection mentioned in footnote 1 on page 28.

Not only does this more complete utilization of the natural source of energy give a special importance to wind power in arid regions; but the design of the propeller part itself can be less complicated and probably more reliable, once the necessity for a constant-speed regulation has been eliminated.

This special condition will not occur in the arid zone if wind power is considered to be the general source of energy and if electricity is relied upon for the distribution of this energy. The fact that there was a time when energy was distributed in Paris by means of a system of compressed air, might lead to a consideration of the possibility of using this method in connexion with compressors driven by wind power machinery. This would offer the same advantage as pointed out for the pumps, that constant speed would no longer be necessary; but such a system would not be able to take full advantage of unforeseen extra power supplied by a stronger wind, because the *total* load on the system would be carried by the power derived from the normal wind. The outlet for unforeseen *extra* power which exists when a wind-driven electric generator works in parallel with a grid is conditional upon the total load of the grid being high as compared to the wind power, so that thermal power stations can reduce their loads and save fuel accordingly, whenever the wind generator produces extra power.

Some combination may be found, nevertheless, in which the advantage of variable propeller speed can be utilized. As matters stand today, the use of wind power in the arid zone is more promising in the field of isolated pumping plants than in that of large-sized central plants, and there is every reason to promote the development of special designs for such plant. In sizes up to 80 or 100 kw. such installations might very well combine the generation of electricity with pumping of water. Of course even the most perfect wind power machinery cannot give more power than is available in the wind and as this power is proportional to the cube of the speed, too much care can hardly be devoted to a selection of suitable sites. As this subject has been dealt with in a number of papers in the collection of the international group, this collection may prove of special importance for the application of wind power in the arid zone. In conclusion the following may be quoted from the foreword: "Enough progress was made under the auspices of the OEEC to justify as a next step the establishment of an International Association for Wind Power which may continue the work of the group on a firm permanent basis".

EXPOSÉ GÉNÉRAL

par

D. Dresden

RÉSUMÉ

Pendant combien d'années encore les combustibles fossiles pourront-ils nous fournir chaleur et énergie en quantité voulue? Les experts sont loin d'être d'accord sur la réponse qu'il convient de faire à cette question, mais ces divergences d'opinion n'ont rien que de naturel, car le problème met en jeu un certain nombre de notions mal définies, notamment celles que recouvrent les mots "quantité voulue", "nous" et "pourront". En effet nul ne peut prédire comment variera la population des pays qui ont ou auront besoin de cette chaleur et de cette énergie ; par suite, nous ne pouvons savoir quel nombre d'êtres humains représente ce "nous". Nous ne pouvons pas davantage prévoir ce que, dans un certain nombre d'années, on considérera comme la "quantité voulue" de chaleur et d'énergie par habitant. Quant au "pourront", tout dépend du prix (en argent, en travail ou en sacrifices) dont on sera disposé à payer l'unité de chaleur ou d'énergie, c'est-à-dire la tonne de charbon ou de pétrole.

En revanche, aucun expert ne nie qu'il viendra tôt ou tard un moment où l'homme devra se passer des combustibles fossiles. C'est un fait qu'en consommant ces combustibles, nous vivons sur notre capital et non pas de nos revenus. Il se peut que nous soyons plus riches, ou plus pauvres que nous ne le pensons ; mais nous aurons beau proportionner nos dépenses à notre fortune, il n'en viendra pas moins un jour où il n'en restera rien.

Il est une énergie d'origine solaire qui existe sous la forme où nous l'exploitons, soit après quelques jours seulement si les cours d'eau qui nous la fournissent sont alimentés par les pluies, soit après un bon nombre d'années s'ils sont alimentés par des glaciers : dans ce dernier cas, en effet, l'énergie primitive est celle qui a produit l'évaporation des eaux qui se sont ensuite déposées en neige au sommet des montagnes.

Il ne faut donc pas craindre de voir cette source d'énergie se tarir ; mais, contrairement au charbon et au pétrole, elle ne peut être transportée là où elle serait le plus utile.

En ce qui concerne l'énergie atomique, les perspectives semblent favorables, bien que de nombreux problèmes restent à résoudre. Grâce à son extrême concentration, cette source d'énergie est infiniment plus facile à transporter que le charbon et le pétrole, malgré la nécessité d'utiliser des récipients protecteurs. Les quantités disponibles de matière fissible semblent considérables ; mais en principe les utiliser équivaut aussi à entamer un capital. En fait cependant le capital est immense, et on peut espérer une solution satisfaisante des nombreux problèmes pratiques que pose son utilisation.

Il est toutefois une autre forme d'énergie solaire que l'on peut assimiler en toute certitude à un revenu, c'est l'énergie éolienne, qui est due à un réchauffement très récent de l'atmosphère par le soleil. L'avantage très séduisant qu'elle présente du fait qu'il n'est pas besoin de ménager un capital s'accompagne d'un grave inconvénient qui tient à sa grande irrégularité en presque tous les points du globe, notamment partout où des vents suffisamment forts (représentant un taux d'intérêt élevé) soufflent par intermittence ; les alizés, beaucoup plus réguliers, sont relativement faibles. En outre il est évidemment impossible de transporter cette source d'énergie ; néanmoins, tout autant que dans le cas de l'énergie hydraulique, les produits obtenus en l'utilisant et peut-être en l'emmagasinant sous quelque autre forme sont transportables.

On s'est longuement demandé si, vu la situation brièvement exposée ci-dessus en ce qui concerne les autres formes d'énergie, on pouvait espérer faire à notre époque des progrès notables en matière d'exploitation de l'énergie éolienne. Il est clairement apparu que la question devait être traitée de deux points de vue différents : *a*) utilisation de l'énergie éolienne pour la production de petites quantités d'énergie en des lieux où la seule autre solution serait d'utiliser un petit moteur à huile lourde ou à essence — une fois la décision prise, il ne faudrait plus tabler que sur l'énergie éolienne ; *b*) utilisation de l'énergie éolienne pour la production d'aussi grandes quantités d'énergie que possible, essentiellement en vue de ménager les combustibles fossiles tant que le vent souffle avec assez de force.

Ces deux modes d'utilisation de l'énergie éolienne n'ont presque rien de commun et il est clair que la question posée plus haut en termes généraux peut fort bien selon le cas comporter des réponses toutes différentes.

En avril 1950, lorsqu'il a été créé un Groupe inter-

national de l'énergie éolienne, il est rapidement apparu à ses membres que l'étude des possibilités offertes dans chacun de ces deux domaines exigerait un gros travail. Ce groupe a récemment publié en guise de rapport final une collection de plus de quarante études techniques.

Dans le premier cas, celui de l'installation isolée de type classique, nous disposons d'un fonds d'expérience beaucoup plus riche que dans le second. En effet, en plus de ce que nous ont appris les anciens moulins à vent que l'on trouve dans nombre de pays et dont plusieurs représentants pittoresques rendent encore service, nous sommes redevables à La Cour de remarquables recherches, effectuées au Danemark dès 1890-1896, sur la transformation de l'énergie éolienne en électricité.

A cette époque, il ne pouvait être question que de courant continu, lequel présente d'ailleurs l'avantage de permettre l'emmagasinement de l'énergie dans des accumulateurs ; de plus il est d'un emploi commode pour la distribution des petites quantités d'énergie dont on avait besoin à l'époque.

Entre 1900 et 1910, plusieurs centaines d'éoliennes du même genre, d'une puissance de 3 à 30 kW, ont été installées au Danemark pour fournir du courant continu à de grands domaines ou à des villages.

C'est seulement depuis quelques années que l'on se préoccupe des possibilités de réalisation de génératrices beaucoup plus puissantes qui permettraient d'économiser du combustible. La construction de ces grandes installations se heurte à un grave problème technique du fait que le nombre de tours de l'arbre de l'hélice doit nécessairement être faible alors que le dessin des pales vise à obtenir une "vitesse spécifique" élevée.

On sait peut-être qu'en Angleterre deux aérogénérateurs de 100 kW chacun ont été construits; mais les résultats obtenus n'ont pas encore été rendus publics. De plus, il faut considérer ces éoliennes comme les prototypes d'installations de 1.000 kW et plus, catégorie d'installations que l'aéromoteur expérimental Smith-Putnam de Grandpa's Knob, dans le Vermont (États-Unis), a contribué à mettre en vedette.

Les deux ordres d'applications font l'un et l'autre l'objet d'études et d'expériences poussées. Dans le cas des installations de petite et moyenne puissance (de 1 à 80 kW) destinées à produire du courant électrique, il s'agit d'abord de perfectionner le dispositif régulateur automatique, de simplifier la partie électrique de l'installation sans nuire à son bon fonctionnement, et enfin de normaliser les pièces de façon à réduire la mise de fonds nécessaire.

En ce qui concerne plus particulièrement les grandes installations, l'un des premiers problèmes à résoudre réside dans la recherche d'un emplacement où l'on obtienne un rapport favorable entre la quantité globale d'énergie éolienne disponible annuellement, et la quantité maximale d'énergie instantanée d'après laquelle on fixera les caractéristiques de l'appareil. Comme le prix de revient de l'énergie électrique produite à partir de l'énergie éolienne ne dépasse guère l'amortissement du capital investi, il importe au plus haut point que, pour une mise de fonds donnée, la quantité totale d'énergie électrique produite chaque année soit aussi forte que possible. Autrement dit, si on se place uniquement au point de vue de la conservation de nos réserves de combustibles, il faut, pour une mise de fonds donnée, économiser le plus possible de combustible avant que l'installation soit hors d'usage.

Dans le cas de ces grandes installations, il n'est pas besoin de se préoccuper de l'emmagasinage d'un excédent momentané d'énergie, car la chose est presque impossible pour de telles quantités. Il en résulte que ces installations n'auront d'intérêt que si elles sont rattachées à un secteur de distribution dont la puissance et la charge soient suffisantes pour absorber à tout moment la totalité de l'énergie que peut fournir un vent favorable.

D'après les renseignements publiés, il semble que l'on soit moins avancé en ce qui concerne les problèmes techniques que pose la réalisation des aérogénérateurs à grande puissance. Il est fort possible cependant que les services d'essais et les bureaux d'études des entreprises qui fabriquent ce type d'appareils se soient activement occupés de ces questions et que les résultats de leurs travaux n'aient pas encore été publiés. Nous avons même de bonnes raisons de croire qu'il en est ainsi ; et il est probable que d'ici quelques années les fabricants pourront indiquer des prix fermes pour des installations complètes dont ils garantiront le bon fonctionnement et dont la puissance dépassera de beaucoup les 100 kW des deux prototypes qui existent actuellement en Angleterre.

Parmi les principaux problèmes de calcul et de construction, il convient de citer celui que pose la réalisation d'un dispositif permettant de laisser fonctionner l'installation lorsque le vent souffle à une vitesse beaucoup plus forte que sa vitesse "normale" à l'emplacement considéré. L'avantage serait double si l'éolienne pouvait en pareil cas conserver un bon rendement ; mais il n'y aurait pas grand inconvénient à consentir un sacrifice sur ce point. L'important est que l'on puisse laisser fonctionner l'aéromoteur sans surveillance permanente, l'orientation des pales de l'hélice en fonction des fortes variations de la vitesse du vent et même des rafales violentes étant assurée par des dispositifs automatiques.

Aucune, ou presque, des considérations qui précèdent ne concerne spécialement la zone aride, et l'on se demandera s'il ne conviendrait pas de modifier nos conclusions générales pour tenir compte des conditions particulières à ces régions. En réalité, la validité de ces considérations ne dépend pas, en théorie, du degré d'humidité ou de sécheresse de l'atmosphère ou du sol ; mais pour ce qui est de la zone aride, il est un autre aspect de l'utilisation de l'énergie éolienne qu'il sied d'envisager plus spécialement. En effet, lorsqu'on emploie une éolienne pour actionner une génératrice électrique, il est hautement souhaitable que le nombre de tours de l'hélice soit aussi constant que possible ; s'il s'agit de produire du courant alternatif triphasé en parallèle avec un réseau de distribution, il devient absolument nécessaire que la vitesse de rotation soit pratiquement constante.

Il en résulte que, dans une période de vents forts, le surcroît d'énergie disponible ne peut être que partiellement capté, puisque, pour en tirer tout le parti possible, il faudrait nécessairement laisser tourner l'hélice beaucoup plus vite.

Il est clair, sans qu'il soit besoin d'exposer en détail l'action du vent sur une pale d'hélice, que le vent qui traverse le plan d'une hélice en mouvement ne peut transmettre aux pales la totalité de son énergie cinétique, car il faut que l'air quitte ce plan, et donc qu'il conserve une certaine vitesse. Or, la fraction de l'énergie cinétique du vent qui est abandonnée à la machine dépend de nombreux facteurs, et notamment du rapport entre la vitesse du vent et la vitesse des pales. Si l'hélice a été conçue de façon à avoir son rendement maximal (c'est-à-dire à capter une fraction aussi élevée que possible de l'énergie cinétique de l'air) pour une certaine vitesse du vent, ce rendement sera plus faible pour toutes les autres vitesses du vent. Il est possible de compenser partiellement cette chute de rendement en modifiant le profil actif des pales (ce qui est le rôle d'un dispositif régulateur bien conçu) ; mais on ne saurait l'éviter complètement.

Or, si l'hélice entraîne, non pas une génératrice électrique, mais une pompe centrifuge, il n'y a aucune raison pour qu'une plus grande vitesse de rotation de l'arbre ne soit pas admissible lorsque le vent est plus fort. A supposer que ce soit surtout pour l'irrigation que l'on souhaite utiliser dans les régions arides l'énergie éolienne, il semble que cette forme d'énergie pourrait être exploitée d'une façon éminemment économique si elle servait à actionner directement des pompes sans l'intermédiaire de l'électricité.

En l'état actuel de la question, l'utilisation de l'énergie éolienne dans la zone aride paraît se prêter davantage à l'exploitation de stations de pompage isolées qu'à l'exploitation de grandes centrales, et il y a toutes raisons d'encourager la mise au point d'appareils spécialement conçus pour cette première utilisation. Dans la catégorie de 80 à 100 kW on pourrait fort bien combiner la production d'électricité et le pompage de l'eau. Bien entendu, même la plus parfaite des éoliennes ne peut fournir plus d'énergie que n'en recèle le vent ; et comme celle-ci est proportionnelle au cube de la vitesse, on ne saurait accorder trop d'attention au choix des emplacements. Comme cette question est abordée dans un certain nombre des documents figurant dans le recueil du groupe international, ce recueil pourra présenter un intérêt particulier en ce qui concerne les applications de l'énergie éolienne dans la zone aride. En conclusion, nous citerons cette phrase du préambule : "Les travaux accomplis sous l'égide de l'OECE sont maintenant assez avancés pour justifier la fondation d'une Association internationale de l'énergie éolienne qui poursuivrait l'œuvre du groupe sur une base solide et permanente."

EXPOSICIÓN GENERAL

por

D. Dresden

RESUMEN

Las opiniones de los expertos varían considerablemente cuando se trata de contestar a la pregunta: ¿Durante cuántos años podrán aún los combustibles fósiles suministrarnos una cantidad adecuada de calor y energía? Esas diferencias de puntos de vista son bien naturales, ya que el problema que estamos examinando entraña algunos conceptos todavía no bien definidos. Ninguno de nosotros puede profetizar en qué medida cambiará el volumen demográfico ni determinar por tanto a qué cantidad de seres humanos se referirá ese "nosotros". Tampoco podemos prever lo que dentro de algunos años se considerará como un suministro adecuado de calor y de energía *per capita*. Y en cuanto al "podrán", depende del precio (ya sea en dinero, en trabajo o en sacrificio) que se esté dispuesto a pagar por una unidad de calor o de energía en forma de una tonelada de carbón o de petróleo.

Por otra parte, ninguno de los expertos niega que llegará un momento en que la humanidad se verá privada de combustibles fósiles. Es un hecho que mientras usamos esos combustibles estamos viviendo de un capital y no de una renta. El capital puede ser mayor o menor de lo que nosotros pensemos, y hasta podemos adaptar nuestro consumo a su volumen, pero llegará un día en que aquél se agote.

Al hacer uso de la energía hidráulica utilizamos una fuerza producida por la energía solar en época reciente, tan reciente a veces que puede datar de muy pocos días (cuando la energía hidráulica se deriva de ríos alimentados por lluvias) o bien de algunos años (como en el caso de los ríos alimentados por glaciares, en cuya formación intervino la energía solar evaporando el agua que se depositó posteriormente en la cima de la montaña).

Por ello no debemos temer el agotamiento de esa fuente de energía, pero en cambio tampoco podemos transportarla a los lugares en los que nos sería más útil que allí donde se encuentra.

Las perspectivas para la utilización de la energía atómica parecen ser favorables, aunque aún quedan por resolver muchos problemas antes de alcanzar una solución que no entrañe riesgos. La facilidad de transporte, debida a la alta concentración de esa fuente de energía, es muy superior a la del carbón y del petróleo, aunque quizá se halle en cierto modo contrarrestada por la necesidad de emplear recipientes protectores. Las cantidades de material fisible existente parecen ser considerables, pero en principio su empleo todavía significa seguir viviendo de un capital. No obstante, en este caso, el capital es tan enorme que se puede esperar una solución satisfactoria de los múltiples problemas prácticos pendientes.

Sin embargo, existe otra forma de energía solar que puede sin duda alguna considerarse como una renta: la energía eólica producida por el calentamiento contemporáneo de la atmósfera por el sol. Sin embargo, la ventaja que resulta de su carácter de renta va acompañada del serio inconveniente de que esta renta es muy irregular en la mayoría de los lugares del mundo, especialmente en aquéllos donde soplan a veces vientos generalmente fuertes (un tipo elevado de renta); los vientos alisios, mucho más regulares, son relativamente débiles. Además, como es natural, no hay posibilidad de transportar esa fuente de energía. Lógicamente, como ocurre con la energía hidráulica, pueden transportarse los productos conseguidos con ella y que posiblemente llevan en sí capturada dicha energía. Se ha debatido bastante la cuestión de si en nuestro tiempo podría organizarse la utilización más a fondo de la energía eólica, teniendo en cuenta debidamente la situación actual en otras esferas de la producción energética, según exponíamos en líneas generales hace poco. Se aprecia claramente que en este problema se plantean dos cuestiones separadas: el empleo de pequeñas plantas generadoras en los lugares en los que, como fuente alternativa de energía, sólo se dispone de otro tipo de fuerza motriz de poca potencia — en esos casos habría que confiar en la energía eólica, una vez seleccionada, como en la única fuente disponible; el empleo de grandes centrales que tendrían como principal objetivo economizar los combustibles fósiles durante el tiempo en que el viento sople con bastante fuerza.

Como estos dos aspectos de la utilización energética son diferentes en casi todos sus detalles, es evidente que la cuestión general anteriormente planteada de "si en nuestro tiempo podría organizarse una utilización más a fondo de la energía eólica" puede muy bien enfocarse de forma diferente en esos dos casos señalados.

Cuando en abril de 1950 se constituyó un grupo

internacional para el estudio de la energía eólica, sus miembros pudieron comprobar rápidamente que era preciso realizar un gran trabajo de investigación de las posibilidades en ambos aspectos. El informe final de este grupo, publicado recientemente, constituye una colección de más de cuarenta documentos técnicos.

En relación con el primero de los aspectos mencionados —el empleo de plantas generadoras individuales típicas— existe mucha más experiencia que con respecto al segundo. Además de los antiguos molinos de viento que existen en varios países y de los que algunos ejemplares pintorescos prestan aún útiles servicios, el profesor La Cour realizó ya en 1890-1896 excelentes trabajos de investigación en Dinamarca, relativos a la generación de electricidad por medio de la energía eólica.

En esa época se trabajaba a base de corriente continua que además poseía la ventaja de poder acumularse en una batería y servía muy bien por tratarse de pequeñas cantidades de energía.

De 1900 a 1910, se establecieron en Dinamarca varios centenares de instalaciones de aprovechamiento de la energía eólica de 3 a 30 kW que suministraban corriente continua a las grandes granjas y a las aldeas.

Pero sólo en años recientes se ha prestado atención a la posibilidad de instalar plantas generadoras más amplias para la economía de combustibles.

Al proyectar esas instalaciones de gran tamaño se plantea un problema técnico muy importante por el hecho de que el número de revoluciones del eje de la hélice es necesariamente reducido, incluso cuando el trazado de las palas se ha concebido con vistas a una "velocidad específica" elevada.

En el Reino Unido se han construído dos centrales de 100 kW cada una, cuyos resultados aún no se han hecho públicos. Además, se trata principalmente de prototipos para centrales de 1.000 kW como mínimo, en cuya clase ha despertado general interés la central experimental de Smith-Putnam, en Grandpa's Knob (Vermont, Estados Unidos).

Ambas posibilidades de aplicación son objeto de serios estudios y experiencias. Con respecto a las plantas pequeñas y medianas (de 1 a 80 kW) destinadas a producir corriente eléctrica, el problema más importante es perfeccionar la regulación automática, simplificando la parte eléctrica de la instalación sin sacrificar su regularidad, y además unificando sus partes componentes con el fin de reducir el costo de instalación.

En relación con las grandes centrales, uno de los primeros problemas que surgen es la selección de lugares apropiados, en los que la energía eólica anual media de que se disponga normalmente suponga una relación favorable respecto de la energía momentánea máxima para la que esté concebida la maquinaria. Como en la práctica el factor determinante del costo de la energía eléctrica producida por la fuerza eólica es el capital invertido en la instalación, es de la máxima importancia que la producción anual total de energía eléctrica sea lo más elevada posible en relación al capital inicial. En otras palabras, y relacionando concretamente este problema con los esfuerzos destinados a prolongar la duración de nuestras reservas de combustibles, es preciso que la central, para un capital dado, economice la máxima cantidad posible de combustible durante la vida de la instalación.

En esas grandes centrales no se plantea el problema de almacenar un excedente temporal de fuerza, ya que las cantidades de que tratamos no lo permiten. Como consecuencia, esas instalaciones solamente serán eficientes si están conectadas a una red de suficiente capacidad y carga para poder admitir toda la fuerza que un viento favorable pueda generar en un momento determinado.

De cuanto se ha publicado, se puede apreciar que donde se ha realizado menor progreso es en el estudio del trazado de las grandes centrales. No obstante, es muy posible que los fabricantes de este tipo de maquinaria hayan realizado trabajos importantes en sus departamentos de experimentación y desarrollo, cuyos resultados aún no se hayan dado a conocer. Existen fuertes razones para pensarlo así y es probable que dentro de pocos años puedan establecerse presupuestos en firme para instalaciones completas de garantizada regularidad para la producción de fuerza muy superior a los 100 kW de los dos prototipos que existen actualmente en el Reino Unido.

Entre los problemas más importantes que hay que tener en cuenta al proyectar una central figura un dispositivo para mantener la instalación en servicio cuando soplan vientos de velocidad muy superior a la "normal" en un lugar dado. Sería doblemente interesante que tales vientos pudieran aprovecharse eficazmente, pero es necesario cierto sacrificio en este sentido. No obstante, debe ser posible dejar funcionar la maquinaria sin una vigilancia continua, confiando en instrumentos automáticos para adaptar las palas de la hélice, etc., a los considerables cambios de la fuerza del viento e incluso a las fuertes ráfagas de aire.

En todo lo expuesto anteriormente, no nos hemos referido concretamente a la zona árida y es justo preguntarse si existe algún motivo para modificar nuestras conclusiones generales con arreglo a las condiciones existentes en esa zona. De hecho, cuanto hemos estudiado antes es válido independientemente de la humedad o de la sequedad de la atmósfera o del suelo. Sin embargo existe otro aspecto de la fuerza eólica al que merece se preste especial atención en la zona árida. Cuando se utiliza un aeromotor para mover un generador eléctrico es muy conveniente mantener lo más constante posible el número de revoluciones de la hélice, lo cual es de absoluta necesidad si se trata de corriente alterna (trifásica) en paralelo con una red.

El resultado es que cuando sobreviene un período de vientos más fuertes sólo puede utilizarse parte del poder adicional ya que una utilización más completa sólo sería posible si se pudiera hacer girar la hélice a mayor velocidad.

Sin necesidad de dar una explicación detallada de la acción del viento sobre las palas de la hélice, está claro que el viento, al pasar por una hélice en movimiento, nunca puede transmitir a las palas toda su energía cinética, ya que el aire tiene que abandonar la superficie de la hélice, para lo cual ha de conservar alguna velocidad. Ahora bien, el porcentaje de la energía cinética transmitida al aparato depende de numerosos factores, uno de los cuales es la proporción existente entre la velocidad del viento y la de las palas. Si la hélice se ha proyectado para que posea el máximo de eficacia a cierta velocidad del viento (es decir, que recoja el máximo porcentaje de la energía cinética del viento), esa eficacia disminuirá con una velocidad diferente del viento.

Esa disminución puede compensarse parcialmente cambiando el perfil activo de la pala (lo que puede conseguirse con un mecanismo regulador apropiado), pero no podrá evitarse por completo.

En el caso de que la hélice no impulse un generador eléctrico sino una bomba centrífuga, no hay ningún motivo para que no sea aceptable en períodos de viento más fuerte una velocidad mayor del eje de propulsión. Suponiendo que el empleo de la energía eólica en las zonas áridas se dedique principalmente a fines de irrigación, resulta que esa fuente de energía puede aplicarse de forma más económica para poner en movimiento bombas sin intervención de maquinaria eléctrica.

En la situación actual, la utilización de la energía eólica en la zona árida ofrece mejores perspectivas si se trata de instalaciones aisladas de bombeo que si se emplean centrales eléctricas de gran capacidad; por ello parece conveniente fomentar el desarrollo de proyectos especiales de estas instalaciones. Cuando su tamaño oscila entre 80 o 100 kW, dichas instalaciones pueden combinar perfectamente la producción de electricidad con el bombeo de agua. Es evidente que incluso el aeromotor más perfeccionado no puede producir más energía que la contenida en el viento, y como esa energía es proporcional al cubo de la velocidad habrá que escoger muy cuidadosamente los lugares apropiados para las instalaciones. Ya se ha tratado de este problema en algunos documentos de la colección preparada por el grupo internacional, que adquiere así gran importancia para el estudio de la utilización de la energía eólica en la zona árida. Como conclusión, puede citarse el siguiente párrafo de su prefacio: "Los progresos realizados bajo los auspicios de la OCEE son tantos que justificarían que el próximo paso fuera la creación de una Asociación Internacional de Energía Eólica a cuyo cargo quedaría de una forma firme y permanente la continuación del trabajo del grupo."

DISCUSSION

Mr. Golding. I am glad that Professor Dresden has described so adequately the work done by the OEEC wind power group, at the meetings of which he presided with such distinction. Although inevitably rather limited in scope, this group succeeded in establishing measuring techniques which could be regarded as standard practice in wind surveys and in exchanging information on the researches being done by several member countries. Another useful activity was the exchange of some novel measuring instruments which enabled them to be compared under different weather conditions. The glossaries and bibliography which were drawn up also provided a good basis and should also be a great help to other investigators. The papers and reports discussed at the OEEC meetings have been assembled in one volume, to which Professor Dresden has referred, and they should serve to provide a useful background to the wind power work which is being done in Europe. It is to be hoped that international co-operation of the kind organized by OEEC can be continued in the future for the benefit of all interested in the subject of wind power.

SOME CONSIDERATIONS AFFECTING THE CHOICE OF AREAS FOR PRELIMINARY WIND POWER SURVEYS IN INDIA

by

P. NILAKANTAN

There are two broad aspects to the problem of utilization of wind power in India. The first is the development of wind power resources for lift irrigation and domestic and small scale community purposes in regions where wind velocities are favourable. This naturally implies a critical examination of wind régimes all over the country and selection of regions where the wind velocities are sufficiently high for economic operation of small and medium sized windmills. The main object of this paper is to examine the extent to which meteorological records and observations can be used with advantage in preliminary surveys.

The second aspect of wind power utilization concerns the selection of the most favourable sites for location of high capacity wind generators. For this purpose broad surveys are not of much use. The survey must be narrowed down to selection of specific points at hilltops or other elevated places. Anemograph stations should also be set up at these places for obtaining continuous records of wind velocities for a period of more than a year. We are not primarily concerned here with this aspect; we shall confine our attention to the first aspect, with special reference to the applicability of available meteorological data.

Apart from official meteorological data and local information regarding wind régimes, the topographical features and geographical factors also determine the distribution and characteristics of surface winds. To date little attention has been paid to this question. The present paper explains the significance of certain geographical features of the Indian peninsula which have an intimate bearing on the existence of localized regions of high wind velocity.

India is a very vast country and the existing weather stations cannot completely cover the whole area even for purposes of a general survey. Moreover, observatories and weather stations are, as a rule, established at urban centres, and the observation of surface winds has not been one of the main considerations in the selection of sites for observatories. Observatories are often located in crowded areas in towns and cities, surrounded by other buildings and tall trees. For surface wind observations these locations are not advantageous since the usefulness of the anemometer readings and anemograph records is impaired.

The topography of any area is an important factor; it sometimes happens that one of the windiest places in the peninsula is within 50 miles of a station that is apparently very calm throughout the year. A typical case is that of Trivandrum, showing an annual average hourly wind velocity of only 4.4 m.p.h. But near the Aruvamozhi Gap, about 50 miles to the south-east, wind velocities of the order of 30 p.m.h. prevail over a considerable period. Again Bihar, West Bengal and Assam appear to have no possibilities at all for windmills. It is, however, known that over the broad rivers and in the mountain gaps in these areas there are localities where comparatively strong winds occur and small-scale operations are economically feasible.

In regard to the use of available meteorological data, two important considerations arise, namely: (a) what correction factors are necessary in order that the observations may be considered as typical of the surrounding area? (b) what are the guiding factors to be considered in selecting areas for preliminary site surveys, apart from the meteorological observations of wind velocities at stations in or around the area?

With regard to the first point, the height above ground of the anemometer cup or pressure tube head, as the case may be, varies from station to station. In practically all cases the actual height is determined by the height of the building or tower on which the anemometer is located. Golding mentions that since wind velocity increases with height above ground, the height of the anemometer used for its measurement is important. He adds that at some stations, adjacent obstructions reduce the wind velocity and for this reason the heights in data provided by these stations are given as "effective heights".

In India the anemometer is generally kept at the top of a mast at a height of about 6-10 ft. above ground level, although anemograph pressure tube heads at aerodromes are often located at a satisfactory height of about 30 ft. above the roof. Often the roof of the building carries the mast but, occasionally, if the building is not sufficiently tall, a small tower is built over it. However, if the anemometer is kept on the terrace of a building it is not clear how the usual formula for gradient of wind velocity over ground level, which is strictly applicable to flow over level ground, can be applied to meteorological records.

Some rough quantative wind velocity surveys were made on the roof of the Belgaum Current Weather Observatory tower at Sambre aerodrome. Here a cup counter type anemometer was located on an octagonal tower, about 10 ft. across, with a surrounding parapet wall approximately 3 ft. high. The anemometer cups were about 4 ft. above the parapet wall and attached to a post fixed to the northern side wall. The wind was westerly and blowing with an average velocity of 26 m.p.h. A vane type anemometer was used to measure the velocity of the wind in a west-east direction at various points on the tower.

The rough velocity survey showed that while above the western parapet wall the maximum velocity was indicated at a height of 4 ft. above the parapet wall, at points further from the wall backflows were set up. The backflow persisted at the eastern end up to a height of about 4 ft. above the wall.

Since the cup anemometer was placed on the northern parapet wall, its readings under the prevailing wind conditions were more or less unaffected. But for a southerly wind, the readings would have been inaccurate. Hence the importance of proper location of anemometers over buildings and towers needs no special emphasis. The height of the cups above the roof should be such that, whatever be the direction of the wind, the effect of the building itself on the wind flow is negligible. The overall height of the anemometer above the ground in such cases has little significance, since the velocity gradient correction can be made only when the flow is over smooth, obstruction-free ground.

It is doubtful whether the effect of constructions can be completely taken into account by the use of "effective heights" as Golding has pointed out in his paper. This is approximately possible if we can set up a mean obstruction level above the ground and consider the height of the anemometer cup above this level. But often the obstructions in crowded areas are of a more serious nature. In such cases the flow in the region of the wake will be highly disturbed and irregular and will not by any means indicate the free wind velocity. A further complication is the movement of branches and leaves which will cause large fluctuations and turbulence. Hence observations made under such conditions cannot be very reliable.

Since we are particularly concerned with anemograph records for preparation of power-duration curves, it should be ensured that the pressure tube heads in all cases are placed sufficiently high above the roof of large buildings and towers to eliminate the effect of all obstructions whatever the wind direction. The best solution is to place the anemometers or pressure tube heads well above all obstructions and at least 30 ft. above the roof. In such cases, the "effective height" may also be obtained easily.

The broad principles governing the flow of air over hills, valleys and plains are fairly well understood. It is well known that over vast stretches of level land without high obstructions, there is always a "good breeze". In crowded built-up areas in the same locality, the wind flow is obstructed and there is "little breeze". The wind blows strongly on elevated places and hills. It blows "over" depressions and valleys which are protected from high winds and storms.

Obviously the most suitable site for a wind generator is an elevated place rising over a stretch of level land without large obstructions in its vicinity and commanding a view of the horizon all around. Some of these points have been dealt with by Golding.[1]

Apart from the characteristics of land contours that are of local significance only, from a more general standpoint, the topography of the country as a whole is of great significance. On the west coast where the Ghats stretch from Bombay to Cape Comorin, it is a remarkable fact that the strongest winds prevail at the "gaps" in the mountain ranges, namely the Goa Gap facing Belgaum and Dharwar, and the Palghat Gap, leading into the Coimbatore district. In the far south the Aruvamozhi Gap is an area of high wind pressure. In the north again there are no mountains blocking the Sourashtra area and strong winds prevail here. Hence in a preliminary wind survey, likely sites are to be found in these mountain gaps and a careful examination of the relief maps should give a clue to the most favourable areas for survey work.

As regards the occurrence of strong winds over large rivers no exact data are available, although there is information regarding the existence of moderate localized winds at certain places over the Ganges and the Brahmaputra. Where such winds prevail, windmills can be used for lift irrigation with advantage. A windmill at Hardwar, which according to meteorological data is not a suitable place, actually enjoys moderate wind over the river. Although the location of this windmill is not very happily chosen, windmills can be used with advantage in the Hardwar area for lifting water from the river. The whole question of wind "regimes" over rivers needs further study and here again the topography of the land is a determining factor.

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1. E. W. Golding. "The Potentialities of Wind Power for Electricity Generator", *Technical Report Reference W/T 16*. The British Electrical and Allied Industries Research Association, 1949.

LES RÉGIONS A CHOISIR POUR LES ENQUÊTES PRÉLIMINAIRES SUR L'ÉNERGIE ÉOLIENNE EN INDE

par

P. Nilakantan

RÉSUMÉ

Le but de cet exposé est de voir dans quelle mesure les observations et relevés météorologiques pourraient être utilisés avec profit dans des enquêtes anémométriques préliminaires sur les sites favorables à l'implantation d'éoliennes de faible et moyenne puissance.

Les stations météorologiques de l'Inde ne peuvent fournir de renseignements, même aux fins d'une enquête générale sur l'ensemble du territoire.

De plus, certaines d'entre elles sont mal situées du point de vue de l'observation des vents au sol, ce qui rend inutilisables les données qu'elles recueillent. La topographie joue à cet égard un rôle très important : à titre d'exemple, la vitesse horaire du vent n'est que de 7 kilomètres à Trivandrum, alors qu'aux environs de la trouée d'Aruvamoshi, à 80 kilomètres seulement au sud-est, des vitesses de 50 kilomètres à l'heure sont courantes une grande partie de l'année.

L'auteur recherche ensuite les facteurs de correction que l'on pourrait appliquer aux données recueillies dans une station mal située pour que ses observations puissent être considérées comme caractéristiques de la région environnante ; il énumère enfin les facteurs à considérer dans le choix des régions propices à des études anémométriques préliminaires.

CONSIDERACIONES PARA LA SELECCIÓN DE LAS REGIONES PARA REALIZAR ESTUDIOS PRELIMINARES SOBRE LA ENERGÍA EÓLICA EN LA INDIA

por

P. Nilakantan

RESUMEN

El objeto del estudio es examinar hasta qué punto los datos y observaciones meteorológicas pueden utilizarse provechosamente en los estudios preliminares para determinar el lugar donde deban instalarse los molinos de tamaño pequeño y mediano para producir electricidad.

Las estaciones meteorológicas de la India no pueden suministrar los datos necesarios para realizar un estudio general sobre la totalidad del subcontinente.

Además, el emplazamiento poco acertado desde el punto de vista de la observación de los vientos de superficie quita toda utilidad a los datos recogidos en algunas de esas estaciones. La topografía de una región tiene mucha importancia en releción con el viento de super-

ficie; por ejemplo, la velocidad del viento en Trivandrum es de 7 Km por hora, mientras que cerca de Aruvamoshi Gap, sólo 80 Km más al sudeste, la velocidad del viento durante gran parte del año es de unos 50 Km por hora.

El autor estudia los factores de corrección que permitan utilizar las observaciones efectuadas por estaciones desfavorablemente situadas, para poderlas considerar como características de la región circundante. Luego, hace una enumeración de los elementos que deben regir la selección de las zonas donde hayan de realizarse estudios preliminares sobre la velocidad del viento.

DISCUSSION

Mr. J. Frenkiel. Dr. Nilakantan dwelt at some length upon the disadvantages of placing wind measuring instruments on roof tops and summarized this position as follows: "There will always be some disturbing effect and the correction factor should in each case be determined by experiment."

Now, the possibility of determining the correction factor implies knowledge of the undisturbed flow at the place of measurement. But no useful purpose would be served by having disturbed flow measured. It is to be concluded that wind measurement on roof tops should be avoided as no correction factors in such measurement can possibly be determined.

Dr. L. A. Ramdas. The meteorological observatories in India are generally situated in towns, most of which are growing. The exposure of wind instruments is as good as possible under the circumstances, and even if new wind stations were to be set up inside cities, no great improvement would be feasible. At observatories on experimental farms the exposure of these instruments is very much better. The meteorologist has his methods of utilizing the available wind data for the purposes of synoptic meteorology, but when he wishes to investigate specially the vertical gradients of wind velocity under ideal conditions he always selects an open clear stretch of ground. The winds along river valleys, referred to in the paper, are just katabatic winds which flow during the night down slopes of hills or mountains, and are a regular feature of mountainous tracts.

Mr. Golding. It was very refreshing to hear Dr. Nilakantan emphasize the need to locate wind measuring stations on well-exposed sites where the topography is such that the wind flow is not artificially disturbed by buildings, trees or changes of slope. This is a most important point which, however, is clearly not appreciated by many people who make wind measurements; so often one finds anemometers placed so that their readings must be falsified by nearby obstructions. If wind survey measurements are to be useful for the estimation of the power obtainable from a windmill mounted on a well-exposed site and at an appreciable height above ground, great care should be taken in siting the instruments. Wind survey measurements which have already been started in India are obviously being made in the right way and an extension of the survey to other coastal districts should afford valuable information on the wind power possibilities in the country.

WIND ENERGY IN INDIA[1]

by

L. A. RAMDAS and K. P. RAMAKRISHNAN

INTRODUCTION

The utilization of wind power for practical purposes has been a favourite theme amongst engineers as well as meteorologists in India [2, 5, 6, 7, 9, 10].[2] An interesting summary of the pioneer investigations by Griffiths [5] and Chatterton [2] of windmills of various types in relation to the critical wind velocities and performance at higher velocities, will be found in Doraiswamy Iyer's scientific note [6]. This paper gives tables containing (a) the mean daily wind velocities for 182 stations in India, based on the daily runs of cup anemometers; (b) percentage frequencies of hours with different ranges of wind velocity at 22 stations for which anemographic data (old Beckley type) were available and (c) percentage frequencies of days with different durations of wind greater than 6 m.p.h. at 15 stations, and also diagrams showing the diurnal variation of wind velocity at 22 anemograph stations and the maximum wind pressure that is likely to be experienced in different parts of India. Taylor's note [10] briefly draws attention to the importance of windmills for pumping water for irrigation and gives a list of various American types of windmills. Raghavan and Sankaran [7] reviewed the progress of investigations on the generation of electric power from wind energy in different countries and stressed the importance of undertaking similar experiments in India. Sil [9] has discussed the actual performance, during one year, of a windmill set up at the Meteorological Office, Poona. Venkiteshwaran [11] has described the various types of instruments that may be utilized for a critical wind survey of India and made very useful suggestions as to how such a survey may be conducted.

Among publications outside India, reference may be made to a recent article entitled "Harnessing the Wind" by E. W. Golding [4] giving a very interesting survey of the technical problems relating to the utilization of wind energy. L. Serra [8] has also made a detailed survey of wind energy in France for the large-scale production of electrical power in that country.

THE VARIATION OF WIND VELOCITY WITH HEIGHT

From the works of Chapman [1], Geiger [3] and others we have some idea of the variation of wind velocity with height in the air layers near the ground. These are based on comparative observations at various levels above ground recorded with anemometers fixed to different types of wind towers of which the Eiffel Tower in Paris (984 ft.) is perhaps the highest. Commonly, in India, anemometers and anemographs record winds at about 50 ft. above ground level. Recent researches on the utilization of wind energy to generate power on a large scale suggest that windmills or other power generating units are likely to be put at much greater heights in future in order to utilize the stronger winds that prevail at higher levels. There is, of course, the problem of putting up such tall structures, but anything up to 300 ft. (about 100 m.) or even 600 ft. (about 200 m.) above ground may not be beyond the reach of future engineering. Further, it may often be possible to locate such power generating units on hilltops which may enable one to reach even higher levels.

While wind surveys with fixed continuously recording instruments may be difficult to achieve at 100-200 m. above ground in the near future and on a country-wide scale, we have at our disposal another means of estimating these wind velocities provisionally from routine pilot balloon observations, which, however, are recorded only 4 times daily in India at a network of about 50 stations. These provide estimates of the

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[1] A paper on "Solar Energy in India" has been contributed by L. A. Ramdas and S. Yegnanarayanan.

[2] The figures in brackets refer to the bibliography on page 55.

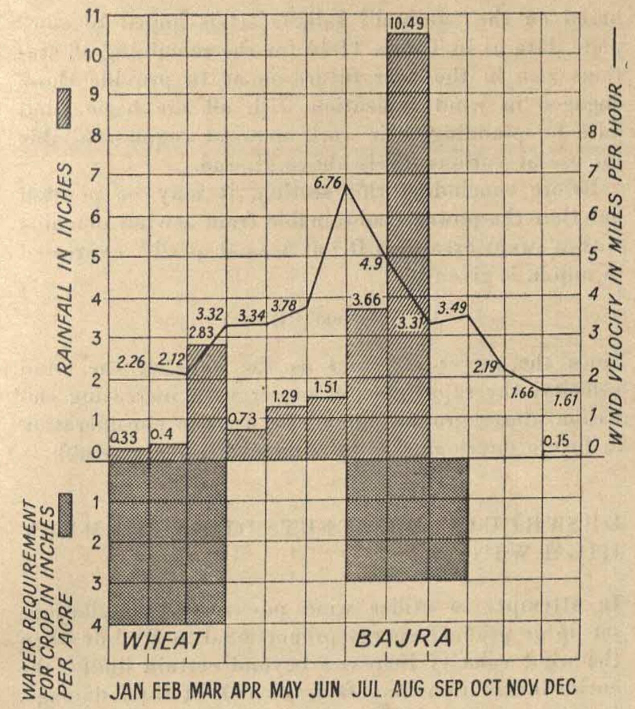

Fig. 1. Average monthly rainfall and wind velocity as recorded in the meteorological observatory at the Indian Agricultural Research Institute, during the year 1952.

wind velocity at heights of 150, 300, 500 metres, etc., up to several kilometres above ground. For our present purpose we may confine our attention to the first 0.5 km. above ground. Utilizing the available wind velocity values it is easy to estimate, by interpolation, the velocities at the intermediate levels.

Sixteen representative pilot balloon stations in India and Pakistan, viz. New Delhi, Jodhpur, Gwalior, Gaya, Calcutta, Nagpur, Veravai, Bombay, Hyderabad, Vishakhapatnam, Venturla, Bangalore, Madras, Trivandrum, Karachi and Lahore have been selected for the purpose of the present report. Values of wind velocity are available for various levels up to 0.5 km. at the 4 hours of observation, which are 2100, 0200, 0400 and 0900 GMT, at the above 16 stations, based on data for periods mostly ranging from 10 to 15 years. From these, tables showing the normal wind velocities at surface 0.1, 0.2, 0.3, 0.4 and 0.5 km., obtained by interpolation, were prepared for the different months of the year. These bring out very clearly the rapid increase of wind speed with height particularly up to 0.2 km. They also show the characteristic diurnal variation with the maximum vertical gradient within 0.2 km. in the night and early morning (2100 and 0200 hrs. GMT) and the minimum vertical gradient in the afternoon. The large vertical gradient of velocity at night is associated with the stratification of the air layers after sunset. The convective turbulence which develops with the advance of day brings about a rapid transfer of momentum from the upper to the lower layers and thereby reduces the vertical gradient of velocity.

From diagrams drawn for each of the 16 selected stations, the number of hours per day when the normal speed exceeds 1, 2, 3, 4 ... 20 m.p.h. has been tabulated for surface, 0.1 and 0.2 km. levels. These tables are too numerous to be reproduced here, but a typical example is given in Table 1; for Jodhpur in the desert zone. For the utilization of wind energy for practical purposes, the number of hours in which wind velocity may be expected to exceed 5, 10 and 15 m.p.h. at surface, 0.1 and 0.3 km. respectively, is given in Tables 2-10. With the aid of these tables, it is a simple matter to compute the total number of hours in each month of the year and the year as a whole, when the wind velocity is likely to exceed 5, 10 or 15 m.p.h.

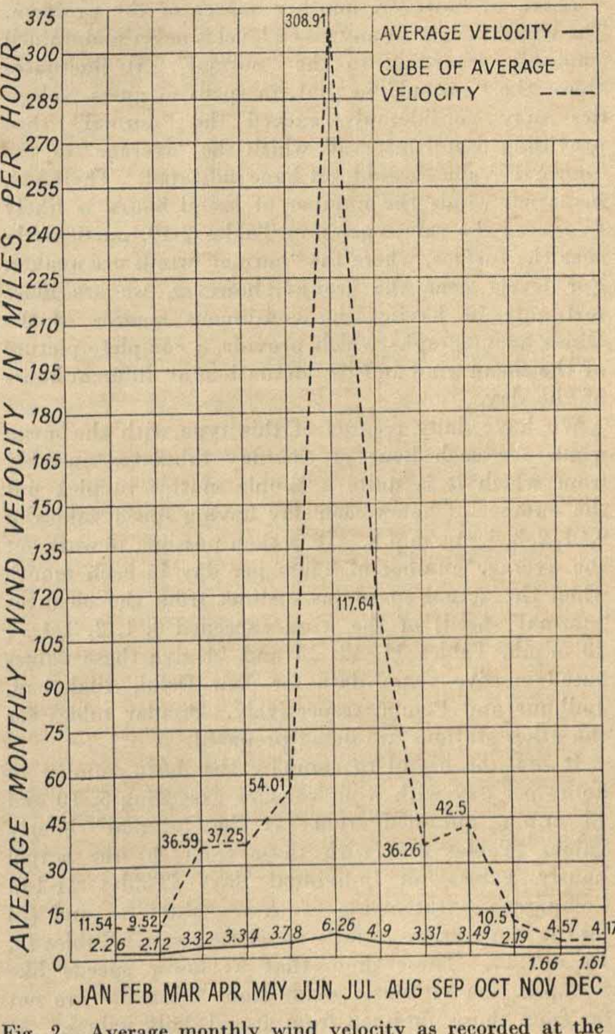

Fig. 2. Average monthly wind velocity as recorded at the Indian Agricultural Research Institute meteorological observatory during the year 1952.

These tables speak for themselves. It is easy to see that at the surface the number of useful hours, as the limiting speed increases from 5 to 10, decreases very rapidly. At 0.1 km. level, winds of 5 m.p.h. blow throughout the day; the number of hours per day with 10 m.p.h. will be quite comparable to those with 5 m.p.h. at the surface. At 0.2 km. level, even 10 m.p.h. speed exists at all hours except at one or two stations. Winds exceeding 15 m.p.h. occur for about half the day. Therefore there is every likelihood of success in running wind machines which begin to function effectively at 10 m.p.h. for generating power, if they are exposed at heights of the order of 0.1 km. The advantage of elevated situations like hilltops also becomes obvious.

The normal wind speeds at various levels and stations so far considered indicate how the efficiency of the wind for power production increases with height above ground.

There is, however, another aspect of the problem. The wind velocity at any given level is never maintained smoothly according to the "normal". It fluctuates about the "normal" so that, in spells of gusts, velocities may considerably exceed the "normal" thus providing useful intervals which the "average" or the "normal" values would not have indicated. Therefore, in actual winds the number of useful hours is likely to exceed the values given in Tables 2-10, particularly near the surface, where the "normal" winds are weaker. For levels near the ground, however, we are more fortunate in having the continuous records of the Dines anemographs which provide a complete picture of the mean wind and its fluctuations at different hours of the day.

We have daily records of this type with the mean winds for each hour of the day tabulated suitably from which it is quite a simple matter to pick out the number of hours each day having speed values of 0,[1] 1, 2, 3, 4, etc. m.p.h. It is then possible to work out the average number of hours per day in each month when the actual speed (as distinct from the mean or "normal" speed) of the wind exceeded 0, 1, 2, 3, 4... 20 m.p.h. Tables 11, 12, 13 and 14 give these values based on five years' data for New Delhi, Allahabad, Jodhpur and Poona, respectively. Similar tables for the other stations are being prepared.

It may be useful to compare the mean number of hours per day with wind velocity exceeding 5, 10 and 15 m.p.h. obtained from (a) the "normal" hourly values (Tables 2-4) with those from (b) the actual hourly values on individual days (Tables 11-14). Comparative statements of these values (a) and (b) for the four stations so far studied are given in Tables 15, 16 and 17. These show that at lower speeds like 5 m.p.h. the estimates made from "normals" are not far from those obtained from actual daily values. At higher limiting values, i.e. 10 and 15 m.p.h., the estimates based on actual values are higher than those based on the "normal" values. It is hoped to complete data as in Tables 11-14 for the remaining 12 stations also in the near future so as to provide those engaged in wind utilization with all the basic wind data for planning their work on wind engines suitable for use at various levels above ground.

Before concluding this section, it may be pointed out that the power P obtainable from a wind machine with a swept area of B ft.^{2} at a wind speed V expressed in m.p.h. is given by :

$$P = 0.0000071 \, B \times V^3$$

Since the power increases as the cube of the wind velocity, the rapid gain of power with increasing elevation above ground should be a basic consideration in future developments in wind utilization research.

DESTRUCTIVE EFFECTS OF EXTREMELY HIGH WINDS

In attempts to utilize wind power, the installations set up do produce energy proportional to V^3; but when the wind velocity increases beyond certain limits, the entire installation may face the risk of total damage. Doraiswamy Iyer [6] has already given a map of India showing the maximum wind pressure experienced in different parts of India (excluding short-lived incidents such as tornadoes and severe thunder squalls). The coastal tracts of Kathiawar and the Konkan on the west and of Andhra, Orissa and Bengal on the east, are the areas with maximum risk to such installations. To supplement the above information we give in Table 18 the maximum gust speed in m.p.h. in each month and for the year as a whole for the 16 stations in India, using all available wind data up to the end of 1952. When we consider the highest velocities ever recorded, even the interior of the country is not free from winds which may occasionally reach speeds of even 100 m.p.h. in short-lived squalls. The engineer will have to take this into consideration in deciding the safety factor for installations for utilizing wind power.

CONCLUSION

We have in this report given a brief survey of the potentialities of wind energy in India. In particular, information provided by the upper winds based on pilot balloon data, has been linked with surface data. It is hoped to complete the computations of the anemographic data for the entire network of stations in the near future. The need is obvious for more anemographs recording at as high levels as may be practicable, at a network of stations in India.

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[1] 0 means less than 1 ; it does not mean that the speed has never been exceeded.

TABLE 1. Mean number of hours per day with wind exceeding specified speed limits (m.p.h.)[1]

Jodhpur

Greater than m.p.h.	*January*			*February*			*March*			*April*			*May*			*June*		
	Sur.	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0,2*	*Sur.*	*0.1*	*0.2*
1	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
2	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
3	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
4	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
5	24	24	24	24	24	24	24	24	24	21	24	24	24	24	24	24	24	24
6	19	24	24	20	24	24	14	24	24	15	24	24	20	24	24	24	24	24
7	11	24	24	5	24	24	7	24	24	8	24	24	18	24	24	24	24	24
8	0	24	24	0	24	24	3	24	24	6	24	24	11	24	24	19	24	24
9	0	23	24	0	24	24	0	24	24	1	24	24	10	24	24	14	24	24
10	0	20	24	0	19	24	0	24	24	0	24	24	5	24	24	12	24	24
11		19	24		16	21	0	18	24	0	24	24	0	24	24	7	24	24
12		16	24		14	18		16	21	0	19	24	0	24	24	0	24	24
13		13	24		12	15		13	16		17	22	0	24	24	0	24	24
14		11	19		9	13		11	14		15	19		24	24	0	24	24
15		6	14		6	11		9	12		13	17		21	24		24	24
16		0	9		2	7		6	11		11	16		18	24		19	24
17		0	3		0	4		3	8		9	14		17	20		17	21
18		0	0		0	0		0	5		7	12		16	19		15	19
19			0		0	0		0	2		5	10		14	17		14	18
20			0			0		0	0		3	8		12	15		12	16
21									0		0	7		11	14		11	14
22									0		0	4		10	13		9	12
23											0	2		8	12		7	11
24												0		6	10		6	9
25												0		3	9		3	7

Greater than m.p.h.	*July*			*August*			*September*			*October*			*November*			*December*		
	Sur.	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*	*Sur.*	*0.1*	*0.2*
1	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
2	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
3	24	24	24	24	24	24	24	24	24	22	24	24	24	24	24	24	24	24
4	24	24	24	24	24	24	24	24	24	15	24	24	17	24	24	24	24	24
5	24	24	24	24	24	24	19	24	24	0	24	24	9	24	24	22	24	24
6	24	24	24	21	24	24	10	24	24	0	24	24	0	23	24	12	24	24
7	24	24	24	1[illegible]	24	24	8	24	24	0	24	24	0	20	23	10	24	24
8	14	24	24	12	24	24	0	24	24	0	24	24	0	17	20	0	22	24
9	12	24	24	10	24	24	0	24	24		19	24		15	19	0	19	22
10	3	24	24	9	24	24	0	24	24		16	23		14	16	0	18	20
11	0	24	24	0	24	24		19	24		14	19		11	14		16	18
12	0	24	24	0	23	24		16	24		13	16		9	12		15	17
13	0	24	24	0	19	24		14	19		10	14		6	9		12	15
14		20	24		17	21		12	17		8	13		0	6		8	12
15		18	22		15	18		10	14		3	10		0	0		0	9
16		16	19		13	15		10	12		0	8		0	0		0	2
17		14	17		9	14		4	10		0	5		0	0		0	0
18		13	16		5	11		2	8		0	1						0
19		12	14		0	8		0	6			0						0
20		10	13		0	3		0	4			0						
21		8	11		0	0		0	0			0						
22		6	9			0			0									
23		3	7			0			0									
24		0	5															
25		0	2															

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[1] Based on normal of hourly anemogram values and pilot balloon winds 4 times a day.

TABLE 2. Mean number of hours per day with wind exceeding 5 m.p.h. (based on "normal" hourly anemogram values)

Surface

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	5	7	8	9	10	11	9	2	5	2	2	2
Bangalore	20	17	15	6	15	24	24	24	24	7	9	22
Baroda	0	0	0	0	18	19	14	14	0	0	0	0
Bombay	20	24	13	16	14	24	24	24	24	20	20	20
Calcutta	4	7	13	24	24	20	15	11	8	4	3	3
Gaya	5	9	10	16	20	16	12	15	8	2	3	5
Gopalpur	10	14	24	24	20	24	24	14	13	12	9	11
Hyderabad	0	0	0	0	8	23	24	20	8	0	0	0
Jamshedpur	0	3	7	9	11	10	9	8	6	3	0	0
Jodhpur	24	24	24	21	24	24	24	24	19	4	9	22
Kodaikanal	23	18	20	22	24	24	24	24	24	19	24	24
Madras	11	9	13	17	24	24	24	24	16	10	14	11
Nagpur	4	4	9	12	20	24	14	12	10	5	0	0
New Delhi	11	23	23	17	16	24	24	14	12	8	9	9
Poona	9	10	11	16	24	24	24	24	19	9	6	5
Visakhapatnam	6	5	8	11	13	11	11	8	5	3	8	6

TABLE 3. Mean number of hours per day with wind exceeding 10 m.p.h. (based on "normal" hourly anemogram values)

Surface

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	0	0	0	1	0	0	0	0	0	0	0	0
Bangalore	0	0	0	0	0	6	8	4	0	0	0	0
Baroda	0	0	0	0	0	0	0	0	0	0	0	0
Bombay	3	6	6	5	4	19	24	24	5	0	0	0
Calcutta	0	0	0	3	6	0	0	0	0	0	0	0
Gaya	0	0	0	6	5	3	0	0	0	0	0	0
Gopalpur	0	0	10	20	3	9	9	0	0	0	0	0
Hyderabad	0	0	0	0	0	1	2	0	0	0	0	0
Jamshedpur	0	0	0	0	0	0	0	0	0	0	0	0
Jodhpur	0	0	0	0	5	12	3	9	0	0	0	0
Kodakanal	0	0	0	0	0	20	18	8	4	0	0	0
Madras	5	0	4	7	11	9	7	6	0	0	6	6
Nagpur	0	0	0	0	2	7	0	5	0	0	0	0
New Delhi	0	5	3	5	4	12	0	0	0	0	0	0
Poona	0	0	0	4	8	12	13	11	7	0	0	0
Visakhapatnam	0	0	0	3	5	0	0	0	0	0	0	0

TABLE 4. Mean number of hours per day with wind exceeding 15 m.p.h. (based on "normal" hourly anemogram values)

Surface

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	0	0	0	0	0	0	0	0	0	0	0	0
Bangalore	0	0	0	0	0	0	0	0	0	0	0	0
Baroda	0	0	0	0	0	0	0	0	0	0	0	0
Bombay	0	0	0	0	0	0	0	0	0	0	0	0
Calcutta	0	0	0	0	0	0	0	0	0	0	0	0
Gaya	0	0	0	0	0	0	0	0	0	0	0	0
Gopalpur	0	0	0	6	0	0	0	0	0	0	0	0
Hyderabad	0	0	0	0	0	0	0	0	0	0	0	0
Jamshedpur	0	0	0	0	0	0	0	0	0	0	0	0
Jodhpur	0	0	0	0	0	0	0	0	0	0	0	0
Kodaikanal	0	0	0	0	0	0	0	0	0	0	0	0
Madras	0	0	0	0	0	0	0	0	0	0	0	0
Nagpur	0	0	0	0	0	0	0	0	0	0	0	0
New Delhi	0	0	0	0	0	0	0	0	0	0	0	0
Poona	0	0	0	0	0	1	3	0	0	0	0	0
Visakapatnam	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 5. Mean number of hours per day with wind exceeding 5 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.1 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	24	24	24	24	24	24	24	24	24	24	24	24
Bangalore	24	24	24	24	24	24	24	24	24	24	24	24
Baroda					Not a pilot balloon station							
Bombay	24	24	24	24	24	24	24	24	24	24	24	24
Calcutta	24	24	24	24	24	24	24	24	24	24	24	24
Gaya	24	24	24	24	24	24	24	24	24	24	24	24
Gopalpur	24	24	24	24	24	24	24	24	24	24	24	24
Hyderabad	24	24	24	24	24	24	24	24	24	24	24	24
Jamshedpur	11	24	24	24	24	24	24	24	24	17	24	13
Jodhpur	24	24	24	24	24	24	24	24	24	24	24	24
Kodaikanal					Not a pilot balloon station							
Madras	24	24	24	24	24	24	24	24	24	24	24	24
Nagpur	24	24	24	24	24	24	24	24	24	24	24	24
New Delhi	24	24	24	24	24	24	24	24	24	24	24	24
Poona	20	24	21	24	19	24	24	24	24	17	22	16
Visakapatnam	15	24	24	24	24	24	24	24	24	24	24	24

TABLE 6. Mean number of hours per day with wind exceeding 10 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.1 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	2	19	21	24	21	19	16	19	12	0	0	0
Bangalore	24	16	16	15	24	24	24	24	24	8	24	19
Baroda					Not a pilot balloon station							
Bombay	7	9	12	9	10	24	24	24	13	1	0	3
Calcutta	0	13	17	21	21	18	24	16	7	4	6	8
Gaya	0	7	24	20	24	20	6	24	0	0	0	0
Gopalpur	8	14	24	24	24	24	24	24	24	24	5	14
Hyderabad	4	10	5	14	17	24	24	24	24	6	8	8
Jamshedpur	0	0	0	0	2	0	0	0	0	0	0	0
Jodhpur	20	19	24	24	24	24	24	24	24	16	14	18
Kodaikanal					Not a pilot balloon station							
Madras	7	0	16	20	24	24	24	24	24	9	19	24
Nagpur	4	12	5	12	9	24	24	20	11	0	0	5
New Delhi	16	24	24	24	24	24	24	18	24	4	6	18
Poona	0	0	1	8	0	19	24	24	16	0	0	0
Visakapatnam	0	3	10	19	20	22	24	19	8	0	0	7

TABLE 7. Mean number of hours per day with wind exceeding 15 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.1 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	0	0	0	9	0	0	0	0	0	0	0	0
Bangalore	8	6	8	0	0	0	24	18	0	0	0	0
Baroda					Not a pilot balloon station							
Bombay	0	0	0	0	0	0	0	10	0	0	0	0
Calcutta	0	0	9	8	7	8	8	6	0	0	0	0
Gaya	0	0	24	0	21	0	0	0	0	0	0	0
Gopalpur	0	0	9	24	24	17	15	0	14	0	0	0
Hyderabad	0	0	0	0	0	24	24	24	1	0	0	0
Jamshedpur	0	0	0	0	0	0	0	0	0	0	0	0
Jodhpur	6	6	9	13	21	24	18	15	10	3	0	0
Kodaikanal					Not a pilot balloon station							
Madras	0	0	0	0	7	24	4	3	0	0	0	0
Nagpur	0	0	0	0	0	0	0	0	0	0	0	0
New Delhi	0	6	6	6	0	0	0	0	0	0	0	0
Poona	0	0	0	0	0	6	12	6	0	0	0	0
Visakapatnam	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 8. Mean number of hours per day with wind exceeding 5 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.2 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	24	24	24	24	24	24	24	24	24	24	24	24
Bangalore	24	24	24	24	24	24	24	24	24	24	24	24
Baroda					Not a pilot balloon station							
Bombay	24	24	24	24	24	24	24	24	24	24	24	24
Calcutta	24	24	24	24	24	24	24	24	24	24	24	24
Gaya	24	24	24	24	24	24	24	24	24	24	24	24
Gopalpur	24	24	24	24	24	24	24	24	24	24	24	24
Hyderabad	24	24	24	24	24	24	24	24	24	24	24	24
Jamshedpur	24	24	24	24	24	24	24	24	24	24	24	24
Jodhpur	24	24	24	24	24	24	24	24	24	24	24	24
Kodaikanal					Not a pilot balloon station							
Madras	24	24	24	24	24	24	24	24	24	24	24	24
Nagpur	24	24	24	24	24	24	24	24	24	24	24	24
New Delhi	24	24	24	24	24	24	24	24	24	24	24	24
Poona	24	24	24	24	24	24	24	24	24	24	24	24
Visakapatnam	24	24	24	24	24	24	24	24	24	24	24	24

TABLE 9. Mean number of hours per day with wind exceeding 10 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.2 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	20	24	24	24	24	24	24	24	24	0	0	13
Bangalore	24	24	24	18	24	24	24	24	24	24	24	24
Baroda					Not a pilot balloon station							
Bombay	10	18	24	15	13	24	24	24	24	3	10	8
Calcutta	11	17	24	24	24	24	24	24	17	10	12	14
Gaya	16	24	24	24	24	24	24	24	24	0	0	4
Gopalpur	16	24	24	24	24	24	24	24	24	24	24	24
Hyderabad	18	21	24	19	24	24	24	24	24	24	24	16
Jamshedpur	0	0	0	6	10	0	16	13	0	0	0	0
Jodhpur	24	24	24	24	24	24	24	24	24	23	16	20
Kodaikanal					Not a pilot balloon station							
Madras	24	15	24	24	24	24	24	24	24	24	24	24
Nagpur	14	19	19	19	22	24	24	24	24	4	14	12
New Delhi	24	24	24	24	24	24	24	24	24	15	16	24
Poona	0	0	5	17	5	24	24	24	24	0	0	0
Visakapatnam	5	7	16	24	24	24	24	24	24	12	14	17

TABLE 10. Mean number of hours per day with wind exceeding 15 m.p.h. (based on "normals" of pilot balloon winds 3 to 4 times a day)

0.2 km. a.g.

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Allahabad	0	9	11	15	12	13	5	0	0	0	0	0
Bangalore	13	9	11	5	7	0	24	24	14	0	0	8
Baroda					Not a pilot balloon station							
Bombay	0	0	0	0	0	0	6	24	0	0	0	0
Calcutta	0	4	12	14	15	14	14	11	10	0	0	0
Gaya	0	0	24	0	24	0	0	0	0	0	0	0
Gopalpur	0	0	12	24	24	24	24	6	19	16	0	0
Hyderabad	0	0	0	2	10	24	24	24	15	0	0	0
Jamshedpur	0	0	0	0	0	0	0	0	0	0	0	0
Jodhpur	14	11	12	17	24	24	22	18	14	10	0	9
Kodaikanal					Not a pilot balloon station							
Madras	0	0	0	0	24	24	22	21	13	0	0	15
Nagpur	0	0	0	8	2	13	24	0	0	0	0	0
New Delhi	0	13	10	10	14	14	2	0	0	0	0	0
Poona	0	0	0	0	0	12	24	21	4	0	0	0
Visakapatnam	0	0	0	0	3	10	20	3	0	0	0	0

TABLE 11. Mean number of hours per day with wind exceeding specified speed limits (based on hourly anemogram values on individual days)

New Delhi

Greater than m.p.h.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
0[1]	24	24	24	24	24	24	24	24	24	24	24	24
1	20	21	21	21	21	23	21	21	19	16	18	21
2	19	20	20	20	20	22	21	20	18	14	17	19
3	17	18	19	18	18	21	20	18	16	12	14	16
4	15	16	18	17	17	20	19	17	15	10	12	14
5	13	14	16	15	15	18	17	15	13	8	9	11
6	11	12	14	14	13	16	15	13	12	7	7	9
7	8	10	12	12	11	14	13	11	10	5	5	7
8	6	8	11	11	10	13	11	10	9	4	4	6
9	4	6	9	9	8	11	9	8	7	3	3	4
10	3	5	8	8	7	10	8	7	6	2	2	3
11	2	5	6	6	5	8	5	5	4	1	1	2
12	2	4	5	6	5	7	4	4	4	1	1	2
13	1	4	4	5	4	5	3	3	3	0[1]	0	1
14	1	3	3	4	4	4	2	2	3	0	0	1
15	0	2	2	3	3	3	1	1	2	0	0	0
16	0	1	1	2	3	3	1	1	1	0	0	0
17	0	0	0	2	2	2	0	0	0	0	0	0
18	0	0	0	1	2	2	0	0	0	0	0	0
19	0	0	0	1	1	1	0	0	0	0	0	0
20	0	0	0	1	1	1	0	0	0	0	0	0

[1] 0 means less than 1; it does not mean that the speed has never been exceeded.

TABLE 12. Mean number of hours per day with wind exceeding specified speed limits (based on hourly anemogram values on individual days)

Allahabad

Greater than m.p.h.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
0	24	24	24	24	24	24	24	24	24	24	24	24
1	21	22	20	22	22	21	20	19	19	16	19	18
2	17	19	18	20	20	20	18	17	17	13	15	15
3	12	15	15	17	17	17	15	14	14	9	10	10
4	10	12	13	15	15	14	12	11	12	6	7	7
5	7	9	11	13	12	11	9	8	9	4	4	4
6	5	7	9	11	10	9	7	6	7	3	2	2
7	3	5	7	9	7	7	5	4	5	2	1	1
8	2	4	5	8	5	6	4	3	4	1	0	0
9	1	3	3	7	4	4	2	2	2	0	0	0
10	1	3	2	6	3	3	1	1	1	0	0	0
11	0	2	1	4	2	2	0	0	0	0	0	0
12	0	1	1	3	2	2	0	0	0	0	0	0
13	0	0	0	2	1	1	0	0	0	0	0	0
14	0	0	0	1	1	1	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 13. Mean number of hours per day with wind exceeding specified speed limits (based on hourly anemogram values on individual days)

Jodhpur

Greater than m.p.h.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
0	24	24	24	24	24	24	24	24	24	24	24	24
1	23	23	22	21	22	21	20	17	16	18	17	22
2	22	21	20	19	21	20	19	15	15	15	13	21
3	21	19	19	17	20	20	18	14	14	13	11	20
4	19	16	16	15	19	19	16	12	13	10	8	18
5	17	13	14	13	18	18	15	10	11	8	6	16
6	14	10	11	11	16	16	13	8	9	5	4	13
7	11	8	9	9	15	15	12	7	8	3	4	11
8	7	5	6	7	13	13	10	5	6	1	2	8
9	6	4	5	6	12	12	9	4	5	1	2	7
10	3	2	3	4	9	9	7	2	3	1	2	3
11	2	2	2	4	8	8	7	2	3	1	2	3
12	1	1	1	3	6	6	5	1	2	1	2	2
13	1	1	1	2	5	5	5	1	2	1	2	2
14	1	1	1	1	4	3	4	1	1	1	2	1
15	1	1	1	1	3	2	4	1	1	1	2	1
16	1	1	1	1	2	1	3	1	1	1	2	1
17	1	1	1	1	2	1	3	1	1	1	2	1
18	1	1	1	1	1	0	2	1	1	1	2	1
19	1	1	1	1	1	0	2	1	1	1	2	1
20	1	1	1	1	0	0	1	1	1	1	2	1

TABLE 14. Mean number of hours per day with wind exceeding specified speed limits (based on hourly anemogram values on individual days)

Poona

Greater than m.p.h.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
0	24	24	24	24	24	24	24	24	24	24	24	24
1	20	21	21	21	24	24	24	24	23	21	19	17
2	18	21	20	21	24	24	24	24	23	20	18	16
3	15	19	18	19	23	24	24	24	22	18	15	13
4	12	17	16	18	22	24	24	24	21	15	13	10
5	9	14	13	15	20	23	23	23	19	12	9	7
6	6	11	11	14	18	22	22	22	17	9	7	5
7	4	8	8	10	16	20	20	20	15	6	4	3
8	3	6	6	9	14	19	19	19	13	4	3	2
9	1	4	4	6	12	16	16	16	10	2	2	1
10	1	3	3	5	11	15	15	15	9	1	1	1
11	0	1	2	2	8	11	11	12	7	0	0	0
12	0	1	2	2	7	10	11	11	6	0	0	0
13	0	0	1	1	5	7	8	8	4	0	0	0
14	0	0	1	1	4	6	7	7	3	0	0	0
15	0	0	0	0	2	4	4	4	2	0	0	0
16	0	0	0	0	1	3	3	3	1	0	0	0
17	0	0	0	0	0	1	1	1	0	0	0	0
18	0	0	0	0	0	1	1	1	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 15. Mean number of hours per day with wind exceeding 5 m.p.h., as estimated from (a) normal hourly values and (b) actual hourly values on individual days.

Station		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
New Delhi	(a)	11	23	23	17	16	24	24	14	12	8	9	9
	(b)	13	14	16	15	15	18	17	15	13	8	9	11
Allahabad	(a)	5	7	8	9	10	11	9	2	5	2	2	2
	(b)	7	9	11	13	12	11	9	8	9	4	4	4
Jodhpur	(a)	24	24	24	21	24	24	24	24	19	4	9	22
	(b)	17	13	14	13	18	18	15	10	11	8	6	16
Poona	(a)	9	10	11	16	24	24	24	24	19	9	6	5
	(b)	9	14	13	15	20	23	23	23	19	12	9	7

TABLE 16. Mean number of hours per day with wind exceeding 10 m.p.h., as estimated from (a) normal hourly values and (b) actual hourly values on individual days.

Station		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
New Delhi	(a)	0	5	3	5	4	12	0	0	0	0	0	0
	(b)	3	5	8	8	7	10	8	7	6	2	2	3
Allahabad	(a)	0	0	0	1	0	0	0	0	0	0	0	0
	(b)	1	3	2	6	3	3	1	1	1	0	0	0
Jodhpur	(a)	0	0	0	0	5	12	3	9	0	0	0	0
	(b)	3	2	3	4	9	9	7	2	3	1	2	3
Poona	(a)	0	0	0	4	8	12	13	11	7	0	0	0
	(b)	1	3	3	5	11	15	15	15	9	1	1	1

TABLE 17. Mean number of hours per day with wind exceeding 15 m.p.h., as estimated from (a) normal hourly values and (b) actual hourly values on individual days.

Station		*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
New Delhi	(a)	0	0	0	0	0	0	0	0	0	0	0	0
	(b)	0	2	2	3	3	3	1	1	2	0	0	0
Allahabad	(a)	0	0	0	0	0	0	0	0	0	0	0	0
	(b)	0	0	0	0	0	0	0	0	0	0	0	0
Jodhpur	(a)	0	0	0	0	0	0	0	0	0	0	0	0
	(b)	1	1	1	1	3	2	4	1	1	1	2	1
Poona	(a)	0	0	0	0	0	1	3	0	0	0	0	0
	(b)	0	0	0	0	2	4	4	4	2	0	0	0

TABLE 18. Maximum gust speed in m.p.h. in each month and year (based on data up to end of 1952)

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Allahabad	36	40	99	61	62	66	52	42	45	51	28	44	99
Bangalore	33	36	41	55	55	51	60	49	38	38	34	35	60
Baroda	30	38	32	36	40	48	54	38	36	42	28	22	54
Bombay	38	38	37	49	64	61	57	48	57	75	80	51	80
Calcutta	45	53	54	71	80	67	50	57	48	67	45	28	80
Gaya	44	42	57	64	88	88	50	51	54	62	27	31	88
Gopalpur	27	37	48	49	50	53	50	46	49	58	35	32	58
Hyderabad	42	50	71	60	65	64	60	52	48	47	35	32	71
Jamshedpur	36	74	57	67	99	69	62	46	49	56	38	30	99
Jodhpur	36	52	60	58	73	90	94	55	50	37	37	39	94
Kodaikanal	54	37	39	51	52	60	67	50	50	54	58	45	67
Madras	34	32	43	42	73	44	54	48	42	56	42	42	73
Nagpur	24	54	48	52	42	82	55	35	36	32	26	20	82
New Delhi	41	52	62	58	70	68	55	48	52	50	37	38	70
Poona	29	30	37	42	54	70	45	58	39	49	34	25	70
Visakapatnam	28	26	35	42	59	43	47	48	45	54	51	35	59

L'ÉNERGIE ÉOLIENNE EN INDE

par

L.A. Ramdas et K.P. Ramakrishnan

RÉSUMÉ

Les auteurs passent d'abord en revue diverses publications relatives à l'utilisation de l'énergie éolienne parues en Inde et dans d'autres pays. Ils pensent que les éoliennes de l'avenir seront probablement placées sur des pylônes très élevés afin de profiter de la vitesse du vent qui augmente avec l'altitude. Ainsi, il sera plus difficile d'effectuer les études anémométriques au moyen d'instruments enregistreurs fixes, mais on pourra évaluer la vitesse du vent à des altitudes de 150, 300 et 500 mètres au-dessus du niveau du sol grâce aux observations que les services météorologiques effectuent régulièrement par ballon-sonde.

Seize stations types de ce genre ont été choisies en Inde. En fonction des vitesses du vent mesurées par ces stations à diverses altitudes échelonnées entre 0 et 500 mètres, on a pu dresser des tables donnant les vitesses normales du vent au sol et à 100, 200, 300, 400 et 500 mètres d'altitude. La figure 1 reproduit le tableau obtenu pour la station de Jodhpur, située dans la zone désertique ; il met en évidence l'avantage des sites élevés.

La vitesse du vent n'est jamais uniforme, mais oscille toujours autour de la normale. Les tableaux 11 à 14 indiquent pour chaque mois le nombre moyen d'heures par jour où la vitesse réelle du vent (par opposition à la vitesse moyenne) dépasse diverses valeurs. Les tableaux 15 à 17 donnent les chiffres obtenus en comparant les valeurs horaires normales (tableaux 2 à 4) avec les valeurs horaires réelles sur certains jours déterminés (tableaux 11 à 14). Il est clair que les évaluations établies d'après les valeurs réelles sont plus élevées que celles qui se fondent sur des vitesses normales de 16 à 25 km/h.

Le tableau 18 indique pour chaque mois et pour l'ensemble de l'année la vitesse maximale des rafales (en miles par heure) pour les seize stations de l'Inde. Il en ressort que, même dans l'intérieur du pays, les vents atteignent parfois des vitesses de 100 miles (160 km à l'heure). Les constructeurs d'aéromoteurs devront tenir compte de données de ce genre dans le calcul des pylônes.

Les auteurs soulignent la nécessité de doter un réseau de stations indiennes d'un plus grand nombre d'anémomètres enregistreurs placés à grande hauteur.

LA ENERGÍA EÓLICA EN LA INDIA

por

L.A. Ramdas y K.P. Ramakrishnan

RESUMEN

Los autores comienzan pasando revista a las obras publicadas sobre la utilización de la energía eólica en la India y en otros lugares. Dicen que es probable que en el futuro los molinos de viento se instalen sobre estructuras altas a fin de beneficiarse de la mayor velocidad del viento reinante a esa altura. Aunque esto puede dificultar la realización de estudios con instrumentos de registro continuo instalados permanentemente, es posible calcular la velocidad del viento a alturas de 150, 300 y 500 metros sobre el nivel del suelo a base de las

observaciones hechas por los servicios meteorológicos con globos sonda.

En la India, se han escogido dieciséis estaciones representativas que utilizan globos sonda para sus observaciones. Partiendo de los valores de la velocidad del viento a diversas alturas hasta 500 m obtenidos por esas estaciones, se han preparado tablas donde figura la velocidad normal del viento en la superficie y a 100, 200, 300, 400 y 500 m de altura. La tabla correspondiente a Jodhpur, en la zona desértica, se reproduce en la figura 1 y pone de relieve las ventajas de las instalaciones en un terreno elevado.

La velocidad del viento no es nunca uniforme, sino que fluctúa alrededor de la normal. En las tablas 11-14 figura el promedio de horas diarias de cada mes en que la velocidad real excedió de la velocidad media. Las tablas 15-17 muestran los valores obtenidos comparando los valores horarios normales (tablas 2-4) con los valores horarios reales de determinados días (tablas 11-14). Evidentemente, los cálculos basados en valores reales son más elevados que los basados en valores normales para velocidades entre 10 y 16 millas por hora (20-26 Km).

La tabla 18 da la velocidad máxima de las ráfagas de viento en millas por hora, de cada mes y de todo el año considerado en su conjunto, comunicada por las 16 estaciones de la India. Se puede observar que incluso en el interior del país la velocidad del viento puede llegar, a veces, a 160 Km por hora. Es preciso que los constructores de molinos de viento tengan en cuenta esos factores al construir las estructuras de soporte.

Se subraya la necesidad de disponer de más observaciones anemográficas a elevadas altitudes obtenidas por una cadena de estaciones.

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DISCUSSION

Mr. Golding. Since wind measurements form an essential basis for investigations on wind power utilization, it is very helpful to have the co-operation of meteorological experts like Drs. Ramdas and Ramakrishnan. The information given in their tables is valuable, but this will have to be amplified by survey measurements at selected sites to ensure that the windiest localities are chosen.

The question of increase of wind velocity with height above ground, for low heights affecting a wind-driven generator, is a complex one because the shape of the hill—usually chosen because of the higher wind speeds on hill sites—greatly affects the air stream near the ground surfaces. There is, therefore, a different law of wind speed variation with altitude, when it relates to a hilltop, from that which applies over level ground. Again, the law will probably alter from one hill to another. In general, the effect of altitude on wind speed up to (say) 100 to 200 ft. is less than that over level ground and the gain may not exceed 10 per cent in many cases.

WIND MACHINES

by

J. JUUL

POWER SUPPLY IN ARID ZONES

Owing to inadequate knowledge of the climate, geography and population of India I am unable to give an outline of the best way of utilizing wind power as an auxiliary means of cultivating the arid zones of India.

Perhaps those interested, however, may be benefited by a general review of the development of power supply for Danish agriculture during the last few decades, to which the first section of this report will be devoted.

Danish farms as a rule comprise 25-40 acres (10-15 ha.) and the greater part of the cultivated area of the country is divided into farms of this size. Seventy or eighty years ago practically all farm work was performed by men and animals. Grain was threshed by flail or by primitive horse-drawn threshing machines.

The grain was ground in privileged, industrial mills, mainly driven by wind power and in a few cases by water power. The windmills as a rule were of the Dutch type with four sails and a swept area diameter of 20-22 m. They produced flour and grit for human consumption as well as groats for domestic animals. At this time about 3,000 of these industrial windmills existed in Denmark, each of them producing what corresponds roughly to about 30 kw., i.e. about 100,000 kw. for the whole country (plate Ia).

Windmills have been used in Denmark and other parts of Europe for more than 700 years. As far as we know Europeans learnt to build windmills from the Orient. The millwright's art was an esteemed and widespread craft and the old-time millwrights knew how to build mills that would work without fail for centuries, although the sails usually had to be renewed every 15-20 years.

Towards the end of the last century agriculture in Denmark was developing quickly and many farmers found it to their advantage to acquire so-called house-mills as a power supply for threshing machines, querns and chaff-cutters.

The house-mills, as a rule, were mounted on the roofs of the barns. They were of primitive construction, made of wood and fitted with four sails mounted with canvas. Especially in the western part of Jutland, which is very windy, nearly all farms were provided with house-mills.

Towards the close of the last century several manufacturers of machinery took up the production of modern house-mills made of iron and steel. Their sails were patent sails (i.e. shuttered sails) with automatic adjustment which caused the mill to turn at a fairly even speed when the vind velocity attained about 7 m./sec. or more.

Roughly about 30,000 of these house-mills were running in Denmark about 40 years ago. Their total production may be estimated as corresponding to about 100,000 kw. Thus the house-mills in conjunction with the industrial mills produced about 200,000 kw. altogether.

About 1890 Professor P. La Cour, a teacher of physics and chemistry at the Askov Folk High School, became interested in the utilization of wind power. Before his appointment as a high school teacher he had been employed at the Royal Institute of Meteorology in Copenhagen, where he took a keen interest in the study of wind power, which at that time was the most important source of mechanical power in Denmark. Considering his work to be of public benefit, the Danish Government granted him a sum of money for the erection of an experimental mill at Askov as well as an annual amount for the purpose of carrying on his experiments. Close to the experimental mill a wind laboratory complete with wind tunnel and instruments was erected, so that wind power research work could be carried out on a scientific basis (plate Ib).

The Askov experimental mill produced electricity for electro-technical purposes as well as for supplying electric light and power to the township of Askov and to the local high school. About 1900 La Cour was able to submit a design of wind power plants for supplying electricity for agricultural and village use.

During the following decade several hundred wind power stations of 5-25 kw. were erected in Denmark according to La Cour's system. The plants most often were constructed for a voltage of 110 or 220, provided with a storage battery of 100-300 ampere-hours capacity, the irregularity of the wind thus being compensated by means of the battery, which would supply current for light and small size motors sufficient for 8-10 days' consumption. Such plants, then, were capable of maintaining a fairly regular supply, even during several days of calm weather.

The running of the wind power plants was so satisfactory and economical that the use of electricity in agriculture became popular. Meanwhile, however, diesel engines appeared and, crude oil being inexpensive, electricity could be produced cheaper by diesel engines which were also less costly than wind power plants. During the years 1910-14 many such diesel engine plants were erected for supplying electricity to villages, farms, crafts and commerce, etc.

The voltage as a rule was 2 × 220 volts, D.C., and the energy 50-100 kw. The area of distribution of these village plants was generally within a radius of 2-3 km. At the outbreak of World War I Danish imports of crude oil were nearly stopped. Consequently many wind power plants were built with 16-18 m. propeller diameter and a maximum energy of 20-35 kw. During the war years a scant supply of electricity was kept up by means of wind power plants, old locomotives and suction gas engines. In Denmark shortly before the war, a very few high tension power stations had been built with steam turbines or big diesel engines as motive power for an A.C. production with a voltage of 10,000/380/220 volts.

After the war these power stations were enlarged at a rapid rate so as to be able to supply electricity to the greater part of the country. During World War II oil supplies to Denmark were again cut off. Hence some of the small diesel plants were replaced by wind power plants while others were provided with rectifiers or transformers so as to be able to receive electricity from such high tension plants as could be run on locally produced fuel, such as peat, lignite, chaff, etc.

Since the end of World War II a radical electrification has taken place, about 10 big steam turbine power stations of 50-250 mw. and 120,000 volts or more supplying A.C. of 50,000 volts tension on the main lines.

For many years the Zealand power stations have been linked up with the hydraulic power of southern Sweden through 50,000 volt submarine cables of 6 km. length, crossing The Sound (a channel between the two countries). During the last few years the capacity of these cables has been materially increased and for the last 2 years a 120,000 volt submarine cable has been in use without breakdowns.

During periods of abundant water supply in Sweden, Zealand gets a large part of its electric power from the Swedish surplus, while during periods when hydraulic power in Sweden is scant or lacking, Sweden receives electricity from the Danish steam power stations. In addition to being linked up with Sweden, the Danish steam power stations are interconnected.

The mutual co-operation between the Danish power works and the Swedish hydraulic power stations has turned out to be particularly expedient. It affords the power works an opportunity to support each other when breakdowns occur and a considerable amount of fuel can be saved because the turbo-generators, when running, nearly always carry their full load.

Nowadays more than 90 per cent of the farmers are provided with electricity, nearly all industry is supplied from the main power works and most private homes also use electricity. In many places 25-30 per cent of the consumers do their cooking by means of electric stoves. Electric heating of rooms is much in vogue during spring and autumn, but only a small minority use electricity for this purpose during the whole of the heating period.

In agriculture electric power is used for threshing, for grinding corn, for working pumps, refrigerators and milking machines, etc. For the purpose of cleaning the milking machines many cowhouses are provided with electrically heated water boilers which supply the necessary hot water.

Nearly all poultry is hatched by means of electrically heated incubators. The chickens are reared by the so-called "chicken-mothers", electrically heated too. Similar equipment is widely used for rearing suckling pigs.

Electric fencing of pastures is extensively used, but the tilling of the soil is nearly everywhere done by tractors, driven by petrol or kerosene motors.

During the last 50 years crops have been more than doubled as a result of intensively mechanized farming methods, and of the introduction of greatly improved species of corn, and also because lucerne and similar crops are being ensilaged. A further reason for the increase of crops is the fertilizing of the soil, partly with stable manure, partly with artificial fertilizers selected according to scientific soil analysis undertaken by authorized laboratories.

Characteristic of conditions in Denmark is the fact that, although the population of the country has increased by about 100 per cent—from 2 to 4 million—since the beginning of this century, the number of persons directly employed by agriculture today is no greater than it was then. The full number of persons representing the increase is employed elsewhere—in industry, commerce, trades and crafts as well as transport service. The transport service is indirectly working for agriculture, fully or partly. Some of the undertakings concerned are established on the profit sharing system.

It might perhaps be natural to ask the question, whether people have become happier through the introduction of mechanical aids and modern working methods.

The answer is that working hours have been reduced, from 10-12 hours a day to 8 hours. Social welfare service has been improved as have education, hospital service and the general state of nutrition. The average duration of life has increased by about 30 per cent.

Dwelling conditions have greatly improved as well, although there is some shortage of housing, building construction having been delayed during World War II owing to lack of building materials.

This development of improved living conditions for a doubled population would have been quite impossible but for the introduction of mechanical aids and the production and supply of electric power which has taken place from the wind motor stage to the present modern electrification, with a network which provides electric power for nearly all the inhabitants of the country.

The electric power supply in Denmark today is a vital factor in the maintenance of the standard of living and the economic life of the Danish community.

Under present circumstances it is necessary to import fuel from abroad to maintain the electric power supply, there being no resources of coal or oil in Denmark. At present, therefore, research is being carried out on the question of supplementing the power supply with wind power, which is the only significant source of natural power in the country and which was formerly of paramount importance, although in a smaller and—measured by present standards—perhaps a somewhat backward community.

It is immediately apparent that the extensive network, built for the distribution of power from main sources of energy to a great number of small consumers, may also be utilized for tapping power from many small sources of energy such as wind power plants. These plants are able to produce cheap electricity from relatively small units, while electric power from steam-driven plants cannot be produced cheaply except by fairly large-sized plants. This creates difficulties for the whole supply if one of the main power units breaks down. Similarly difficulties will arise when increase and extension of the power supply takes place by leaps and bounds. Any power supply from a few big units is more vulnerable than one from a great number of small units.

Wind power plants built for parallel working and connected with large networks are advantageous in that they can be exploited to a far greater extent than the wind power plants of the past. The reason for this is the fact that large networks can receive the full production both night and day without necessitating a reduction of output or the stopping of the mill as was often the case with the old-fashioned wind power plants. They produced D.C. for small areas of supply which had very limited storage possibilities only and the need for uniform tension demanded reduction of output when the wind velocity suddenly increased.

From the facts enumerated above it will be seen that the present stage of power supply in Denmark has been reached by detours, partly because demand has developed gradually, partly because electro-technics have developed with demand.

It should then be possible to develop a power supply for arid zones along more direct lines and in a less expensive manner than has been done in Denmark, as it is now possible, from the very start, to use more perfect technique than was known when the electrification of Danish agriculture was embarked upon.

The profit sharing system is widely accepted among the country population in Denmark. Hence the electric power of Danish agriculture is almost exclusively supplied by profit sharing enterprises, and dairies, slaughter-houses, commercial enterprises and various manufacturing undertakings are run on this system.

The electric power of cities and towns, on the other hand, is nearly everywhere purveyed by municipal works.

Safety measures and supervision of power plants are the concern of an electricity board, organized by the government, and which has a certain amount of authority regarding the allotment of areas of distribution to the various power stations. The power stations are under an obligation to consult the board when contemplating increases of machine power or when placing orders for new acquisitions of any size. The power stations are practically all of them members of Danske Elværkers Forening (Association of Danish Power Stations) which looks after the common interests of its members.

THE USE OF WIND POWER FOR PRODUCING 3-PHASE A.C. FOR AN EXISTING A.C. NETWORK

The experiments and research work described below derive from the work, not yet completed, which I have carried on since 1947 for Sydøstsjællands Elektricitets Aktieselskab (abbreviated SEAS), township of Haslev, Denmark.

The work has been done mainly under my direction and SEAS has issued no report on the subject. Whatever has so far been published and all that is stated below represents my own personal experience and views and should not be considered an official report.

SEAS is an electric power supply company with its own steam power plant of 90 mw. which supplies electric power to the southern part of the Island of Zealand and the greater part of the Lolland-Falster Islands. The SEAS power works are interconnected with the other Zealand power stations and those of Københavns

Belysningsvæsen (The Copenhagen Lighting Service). All these power works together are interconnected with the hydraulic power stations of Sweden.

The research work has been divided into the following sections: (a) Measuring of wind energy. (b) Wind tunnel investigations of rotor blades. (c) Building the experimental mill. (d) Efficiency and energy production of the experimental mill. (e) Determination of the effect of wind upon wind motors. (f) Construction of future wind power plants. (g) Economics of future wind power plants.

MEASURING OF WIND ENERGY

The energy of the wind is influenced by many different factors, and widely different circumstances make it necessary to study the characteristics of the wind and its influence upon climate, buildings, drifting of snow and soil, the sheltering effects of woods, trees, etc., and the utilization of wind power for the production of energy.

My research work has been related to the last mentioned subject only, and has been confined to investigation of such wind conditions as are of special practical importance to the building of wind power plants.

Wind conditions in western Europe are strongly influenced by the continent east of it and the Atlantic Ocean west of it. Above the Atlantic, atmospheric low pressure centres often arise, which move to the eastward and dissolve in eastern Europe, where high pressure centres will often occur.

The prevailing winds, therefore, are westerly, but when the high pressure centres above northern Russia are dominant, fairly strong and continual easterly winds may occur, especially during the winter, with a velocity which, however, rarely rises above 20 m./sec. To the south-westward, storm centres with a wind velocity of about 30 m./sec. sometimes arise and very rarely—at intervals of several years—the velocity may reach 40 m./sec. or more.

The strength and character of the wind depend very much upon its direction, whether it blows across sea or land towards the point of observation. When blowing across land it will generally meet obstacles in the shape of uneven ground, forests, groves or buildings which cause eddying and turbulence and reduce average velocity, while wind coming across the open sea is less turbulent, its swirl not being noticeable to the same heights as that of the land wind.

The objects met by the wind considerably influence its flow both in front of them, beside them and above them up to distances from the objects concerned corresponding to their width and height. Within the area horizontally and vertically limited by these dimensions, swirl of the wind will arise which is perceptible behind the objects, even at a fairly great distance.

Trees and buildings cause the wind to be rough and puffy up to 30-40 m. height above ground, while hills and mountains cause turbulence up to very great heights. The heating of the ground surface by the sun causes air currents to go upwards, producing swirl and turbulence. Hence the working capacity of the wind is greatly dependent upon local circumstances and upon the height at which it is intended to utilize it.

The specific weight of air at 15° C. and 760 mm. barometric pressure is 0.00122. Thus 1 cubic metre of air under the same conditions will weigh 1.22 kg. This weight varies according to the following formula:

$$\text{kg. per m.}^3 = 1.3 \times \frac{P}{760 \times (1 + \frac{1}{273} \times t)}$$

P being barometric pressure in millimetres and t the temperature in degrees centigrade.

As the temperature of the air may alter, e.g. from —30° to +40° and the barometric pressure from 720 to 780 mm., theoretically there is a possibility of the weight of the air varying up to about 25 per cent. A variation of more than about 15 per cent, however, will rarely occur in most low-lying places.

In mountainous tracts the working capacity of the wind will be influenced by pressure decrease with altitude.

The wind energy is proportional to the weight of the air and the cube of the wind velocity and is expressed by the formula:

$$a = \frac{m \times V^3}{2}$$

m being the mass, which in this case may be numerically expressed by the formula:

$$\frac{1.22}{9.81}$$

1.22 being the weight of the air in kg. per m.³ at 15° C. and 760 mm. barometric pressure and 9.81 being the acceleration of gravity constant.

The inertia of the wind having to be transferred to moving mechanical elements, only part of the wind energy can be utilized. Hence there will be a point in the retardation of the wind at which the energy transferred from the inertia of the wind to the parts moved by the wind will be greatest. The factor of most favourable retardation is found to be 0.6.

When reckoning with a wind column of 1 m.² cross section area, the theoretical capacity of the wind will be:

$$\text{kg. m./sec.} = \frac{1.22}{9.81} \times \frac{V^2}{2} \times 0.6 \times 1 \times V$$

or

$$\begin{aligned} \text{kg. m./sec.} &= 0.037 \times V^3 \\ \text{h.p.} &= 0.000493 \times V^3 \\ \text{watt} &= 0.37 \times V^3 \\ \text{kw.} &= 0.37 \times \left(\frac{V}{10}\right)^3 \end{aligned}$$

When reckoning with a cylindrical wind column,

$$\text{kw.} = 0.000285 \times D^2 \times V^3.$$

A wind motor, however, like any other power machine, will be unable to transform the total energy imparted to it, but has an efficiency factor depending upon blade construction and blade tip speed in relation to wind velocity and upon the possibilities of adjustment of the characteristic of the wind motor to that of the machinery driven by it.

The efficiency of a wind power plant is:

$$E = \frac{\text{Energy rendered kw.}}{0.000285 \times D^2 \times V^3}$$

The speed of the wind is practically never steady, but will vary from 6 to 10 m./sec. at short intervals; it is therefore necessary to calculate with mean values, in this case 8 m./sec.; this will, however, entail an inaccuracy when computing the wind energy, 8^3 equalling 512 whereas $\frac{6^3 + 10^3}{2} = 608$, thus the actual average wind energy exceeds the measured energy by about 20 per cent.

For the purpose of measuring wind velocity and wind energy anemometers are used. Formerly, instruments were used which indicated wind velocity mechanically. For the research work carried out by SEAS, small electrical anemometers, as shown in plate Ic have been used. They consist of a small windmill driving a suitable A.C. generator with rotating magnet and fixed induction coil. The generator will produce an A.C. tension which bears a definite proportion to the revolutions per minute of the mill and to the velocity of the wind which acts upon it. The tension is carried to a voltmeter by means of a wire of suitable length according to circumstances, so that the outfit may be used for long-distance measuring if need be.

Moving coil apparatuses mounted with suitable rectifiers are used as voltmeters, because they need little energy for giving very distinct deflections. Hence there is no difficulty in turning a voltmeter of this type into an automatically registering apparatus which will trace a curve on a tape moved by clockwork. The curve indicates the variable wind velocity in positive and negative values, thus depicting turbulence and character of the wind. For the determination of average values hour by hour a scale, specially graduated for the apparatus in question, must be used.

When the wind energy within a certain period of time is to be determined, the number of hours of various definite velocities must be counted and the energy computed.

An electrically working anemometer of different design has also been used to some extent. It consists of a horizontally rotating windmill, which gives off an electrical impulse—derived from an independent source of power—every time a certain length of wind column, e.g. 100 m., has passed it. The impulses of each time unit are counted by a separate instrument. By means of the number of impulses the average wind velocity per hour can be computed.

As mentioned above, the wind energy computed from the readings of these apparatuses will not be absolutely exact, because the variations of wind energy, caused by the cubic function of the velocity, cannot be taken into account when making out the energy. When measuring wind velocities at 12 m. height along the Danish seashore, the discrepancy amounts to a few per cent. When measuring further inland in rather strongly turbulent wind, the discrepancy will materially increase. The discrepancy can be eliminated by using an anemometer of French design, used by Électricité de France (plate Id). It consists of a vertical axis wind motor, pulling a small A.C. generator, the production of which is measured by a Ferrari meter, adjusted for indicating kwh. per m.^{2} swept area. This instrument indicates the energy of turbulent wind with a fair degree of accuracy.

Comparative measurings have been carried out with anemometers of the three different designs, at the SEAS experimental station at Vester Egesborg. The results are shown in the following table, numbers *1* and *2* being the measurings of the two apparatuses first mentioned and number *3* those of the one last mentioned:

	1	*2*	*3*
1953			
July	137	134	141
August	148	142	161
September	127	130	146
October	87	51	63
November	180	142	159
December	46	28	83
1954			
January	168	164	219
	893	791	972

As already stated the number *1* figures are based on an estimated wind velocity from hour to hour. In very turbulent winds it is sometimes difficult to ascertain the correct figure, hence inaccuracies may occur in the computation.

In the estimates and computations set forth in the following sections of this paper, measurings by the first-mentioned apparatus are used, a certain knowledge of the character of the wind and of the maximum and minimum figures of its velocity being necessary for the purpose of determining its pressure and energy.

When measuring wind energy and dealing with wind conditions on the whole, it is difficult to obtain exact figures. Hence it will often be necessary to make do with average values of a fairly great number of readings and therefore to look at the results with a certain tolerance.

If, for instance, the capacity of a wind motor at different wind velocities has to be estimated by means of an anemometer of the directly readable type, mounted in the vicinity of the wind motor, it has to be taken into account that the turbulence of the wind is to a certain extent compensated by the comparatively large size of the swept area of the rotor, while practically no compensation of turbulence takes place where the very small swept area of the anemometer is concerned.

When the annual wind energy available in a certain locality is to be ascertained, the most accurate results will be obtained by means of an apparatus of the French type (number *3* in the above table), but it is necessary, also, to get some indication of the turbulence of the wind on the particular site, since it influences the capacity of a wind motor.

Wind energy increases according to height above ground, hence inland wind energy at 50 m. height will be about twice that at, for instance, 20 m. height. Where sea wind is in question the increase of energy according to height is less, as strong winds blow across the sea at lower heights above the surface. The most favourable wind conditions are generally to be found on flat coastal tracts without trees or buildings.

Definite rules applying to increase of wind energy according to height cannot be laid down, the wind energy depending upon the nature of the ground and the frequency with which the wind blows from the various quarters. It is obvious, furthermore, that the energy deriving from wind blowing during a great number of hours at velocities of 6-10 m./sec. will be more valuable than a corresponding energy due to high wind or a strong gale lasting a few hours.

When calculating the height at which utilization of wind energy will pay best on the site chosen for erection of a wind power station, measurings must be taken by automatic anemometers over a prolonged period and at different heights above ground to determine the increase of wind energy according to height. A systematic measuring of energy of this kind has not yet been carried out in Denmark, but is being prepared. The measurings will be undertaken on a 50 m. mast at heights of 12, 25 and 50 m. by means of an automatic anemometer, which will record maximum and minimum velocities as well as duration (in hours) of the various velocities. Furthermore the annual energy in kwh. per m.^{2} will be measured by means of suitable apparatus. Up to now, wind energy in Denmark has been measured at heights of 12 and 33 m., the results being calculated in kwh. per m.^{2}.

The amount of energy to be extracted from the wind will depend upon the character of the wind motor and its adjustment to the machine it is driving.

A wind power plant constructed to produce the greatest possible energy for a large area which can take delivery of the maximum energy possible at any time, should be designed with a view to these circumstances. A power plant intended for supplying a smaller area, with limited possibilities of consumption and storage, should be designed accordingly.

When working out an advance estimate of energy produced, it is necessary to know, month by month, the annual total number of hours of the various wind velocities. Hence, wind energy must be measured so as to obtain a knowledge of the number of hours during which the various velocities occur, in addition to obtaining results concerning annual amount of energy per unit area and annual average wind velocity.

WIND TUNNEL INVESTIGATIONS OF ROTOR BLADES

Up to 1925 the sails of wind motors had shapes and profiles formed along the lines of older models, to some extent modified according to the purpose of the windmill.

The old time four-sailed Dutch windmill had slightly twisted sails and a fairly great tip-velocity of up to 2½ times the wind speed. These mills had only a small starting torque and best served as motive power for machines that would start without any load, such as querns and dynamos.

The so-called wind wheels with many plane blades of fairly heavy weathering were quite different. Owing to the heavy weathering they had a rather pronounced starting torque and a relatively low blade tip velocity which as a rule did not exceed the wind velocity. This type of wind motor is specially suited for driving machines which are slow going and heavy to start, like piston pumps.

The efficiency of the mills of the Dutch type could be raised to about 30 per cent of the theoretical energy of the wind, while those of the latter type could hardly attain more than 15-20 per cent.

The production of aeroplanes encouraged the study of aerodynamics by means of elaborate scientific research. Thus the present day aerofoil was developed, and it became obvious if windmills were made with blades of streamlined cross-sections they could be made considerably more efficient.

Conditions pertaining to aerofoils, however, are not quite identical with those pertaining to the blades of a wind motor. The aerofoils are exposed to a fairly even current of air, the speed of which is the same at the root and at the tip of the aerofoil, and it is of paramount importance that the foil be made as light as possible. Where the wind motor blades are concerned, the speed of the wind varies in relation to that of the blade, from a maximum at the extreme end to a minimum at the blade root. Blades revolving on a horizontal axle are exposed, in addition, to the positive and negative effects of gravity upon the material of which they are made and furthermore to the centrifugal force produced by their rotation. The weight of the blades, on the other hand, is not of such decisive importance as that of the aerofoils.

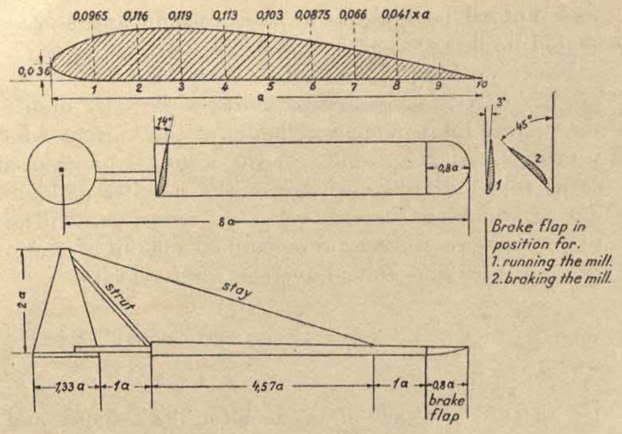

Fig. 1. Proportions of blade design.

The first streamlined blades in Denmark appeared about 1925 on the Agrico Windmotor designed by Poul Winding, a Danish engineer. Later on the (Danish) firm of F. L. Smidth produced the so-called Aeromotor which was fitted with streamlined blades of American type.

To investigate the properties of various shapes of blades, an interimistic wind tunnel with a cross-section area of 2.6 × 3.5 m. was constructed. By means of a 90 h.p. electromotor of adjustable speed and mounted with a propeller, a wind of velocity up to 6 m./sec. could be produced. In the middle of the tunnel on a frame offering very small air resistance a 0.5 h.p. dynamo, excited from outside, was mounted; on its axle, blades of various types could be fitted.

The dynamo was provided with tachometer, voltmeter and ammeter as well as an exciter-control by means of which a load could be imparted to the blades, corresponding to any blade tip velocity arbitrarily chosen within the limits of practical possibility. Thus it was feasible to state the efficiency of the various blade types at different wind velocities.

However, results obtained in the tunnel are not immediately comparable to the efficiency attained by the same blades in open air, the wind in the latter case being free to circumvent the swept area, whereas this is not the case inside the tunnel, unless the tunnel cross-section area greatly exceeds the swept area of the blades.

About thirty different blade types were tried. Most of them could be immediately condemned as unsuitable. The most effective shape had the profile shown in Fig. 1, and experiments proved twisting and shape of blade tips to be of signal importance. To start the blades turning at about 5 m./sec. wind velocity, they required a twist at the tips of about 3°, increasing evenly to about 16° at the blade roots.

In Fig. 2 is shown the influence of blade tip shape on efficiency. Experiments showed that maximum efficiency was obtained with a semi-circular shape of the extreme blade tip, the shape of the profile being pointed so as to make a sharp edge at the end of the tip.

Owing to the necessity of fitting wind motor blades with contraptions for adjustment, experiments were made with the mounting of various gadgets suitable for adjusting the effectivity of the blade and for braking it when stopping the mill.

It appeared that contrivances mounted on the surface of the blade, and altering its shape so as to deviate from the ideal shape, had the effect of considerably reducing the efficiency of the mill. Hence the brake flaps should be absolutely flush with the surface of the ideal shape blade when a braking of the mill is not intended. Contrivances for governing the brake flaps should therefore be placed within the body of the blade. It was ascertained, likewise, that the brake flaps need only be a very small part of the blade and that it is unnecessary to construct the blade for turning round its longitudinal axis in order to obtain a braking which will either stop the mill or reduce its efficiency as desired or its revolutions per minute in high wind.

The width of the blade in relation to its length does not appear to be of such decisive importance as the other proportions of the blade. A width at the blade root of about one-tenth and at the extreme end one-seventeenth of the length appeared to be sufficient for producing the greatest possible efficiency. A materially increased width did not affect the efficiency. If for practical reasons of design it is preferred to give the blade a rectangular shape, this did not appear to influence the efficiency.

Fig. 3 shows how conditions differ between 2-, 3- and 4-bladed mills.

Presuming that a mill is running at its most favourable blade tip velocity the energy of a 3- or 4-bladed mill will exceed that of a 2-bladed one by a few per

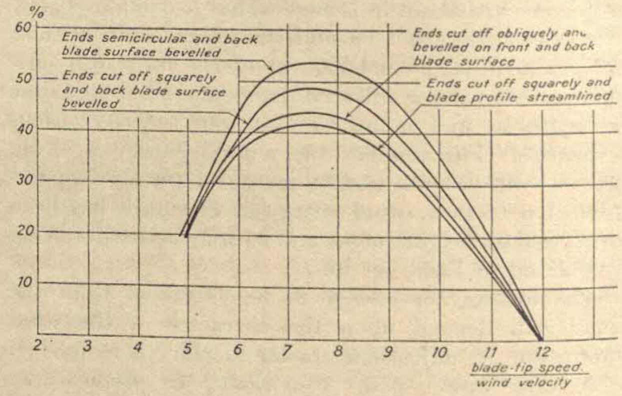

Fig. 2. Effects of wind motor with two streamline-sectioned blades when blade-end shapes are of four different designs, effects measured in wind tunnel and expressed in per cent of total wind effect.

cent only. When the blades are turning at a tip speed somewhat below the most favourable, a considerably greater efficiency is obtained by means of three or four blades than by two blades only, although the difference is not proportional to the number of blades.

BUILDING THE EXPERIMENTAL MILL

The purpose of building the SEAS experimental mill at Vester Egesborg was:

1. To attempt the running of a three-phase A.C. generator with a windmill as the prime mover and connected to an A.C. network already existing.
2. To test—in the open air—the blade constructions which in a wind tunnel had proved most suitable for the purpose in question.
3. To investigate how great an effect per unit area is obtainable within the area circumscribed by the blade tips (the swept area).
4. To ascertain the annual production obtainable per unit swept area.
5. To find by experiment (a) the most advantageous blade-tip speed; (b) a blade adjustment contrivance, (c) the necessary automatic action.
6. To measure the maximum wind pressure on the windmill axle.

A propeller of 8 m. diameter was chosen. Decisive for this choice was the fact that it would be more difficult to experiment with a still bigger windmill which, in addition, would be more expensive to build. As the experiments aimed at ascertaining the magnitude per unit swept area of the various factors, the size chosen was considered to be sufficient for the purpose. The height of the tower was fixed at 12 m., the preceding wind pressure measurements having been made at this altitude.

The tower is supported by stays fixed to a collar—7.5 m. above ground level—inside which the tower will turn according to the direction of the wind.

The foot of the tower rests on a step bearing on a spring-mounted lever. To this lever is fixed an automatically registering pressure gauge, so that the pressure on the step bearing produced by the pull on the stays can be measured.

The pull on the stays is produced partly by the pressure of the wind on the tower itself and partly by the pressure deriving from the retardation of the wind as it drives the mill.

On the top of the tower is a cabin in which the main axle of the mill is mounted. On the axle is a chain drive to an intermediary axle from which the generator is driven, also by a chain. The main axle, furthermore, is fitted with a braking device.

The lower part of the tower goes through the roof of a small house, built on a concrete foundation, on which the step bearing unit rests. Furthermore, a cog wheel rim has been fixed to the concrete of the foundation, concentric with the step bearing. On the tower, and in gear with the fixed rim, is mounted a cog wheel which is driven by a small motor. This motor is governed by a vane which is mounted on the tower and which sets the motor going either way, thus keeping the mill facing the wind.

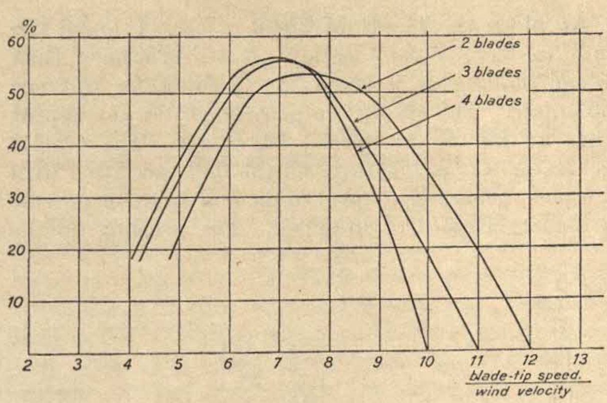

Fig. 3. Effect of wind motor of 2 m. propeller diameter and with streamline-sectioned blades, measured in wind tunnel, and expressed in per cent of total wind effect.

The blades are constructed as shown in Fig. Ie and are of a shape found by wind tunnel experiments to be suitable. The extreme part of each blade is constructed as an adjustable brake flap the axle of which will move about 60 mm. lengthwise in a link motion, thereby turning the flap 90°. Thus the flap may be fixed either flush with the blade surface or perpendicular to it.

The flap axle is operated by a wire passing through the cavity of the blade to the main axle where a lever system transmits the movement to a pulling rod through the main axle of the windmill which is bored.

The pulling rod in the axle is governed by the piston of an air-pressure cylinder; hence the mill can be adjusted for running by letting compressed air into the cylinder thus simultaneously disengaging the brake.

The inlet of air into the cylinder is regulated by an electromagnetically governed valve which opens the inlet as soon as the electromagnet is energized, shutting off the vent of the cylinder at the same time.

By the beginning of 1950 the experimental mill was ready for use. It was at that time fitted with two coupled-up generators, one of them being 6-polar, the other 4-polar. The generators were connected to the network by means of a wind pressure relay so as to couple up the 6-polar one at about 5 m./sec. wind velocity. At about 8-9 m./sec. wind the relay would switch over so as to throw out the 6-polar generator and couple up the 4-polar one. With slackening of the wind, the wind pressure relay would switch back to the 6-polar generator.

By means of this contrivance and by altering the gear ratio between the mill main axle and the secondary axle, investigation of the efficiency and the characteristics of the mill at various constant blade tip speeds became feasible.

At blade tip speeds of 35-40 m./sec., I found the mill to have a considerably greater efficiency than when running at a blade tip speed of for instance 60 m./sec. The use of two generators did not appear thus to be of any special advantage. The 4-polar generator was dismantled and the mill was fitted with a 6-polar generator coupled to the mill so as to provide a blade tip speed of 38 m./sec. For coupling up the generator a centrifugal governor—instead of the wind pressure relay—was used. This governor would switch the generator on to the network as soon as its speed became synchronous.

It was brought out, furthermore, that in this manner the mill became self-adjusting if coupled to an A.C. generator with a kipping point high enough to prevent the mill from loading the generator above it. Under these circumstances the generator will force the mill to run at a constant speed—apart from fluctuations of a few per cent caused by the slip of the generator. From the characteristics of the mill it appears that its efficiency attains optimum at a blade tip speed of 5-6 times the velocity of the wind. At 38 m./sec. blade tip speed the efficiency factor thus reached its optimum at 6-7 m./sec. wind velocity. At increasing wind velocity the efficiency will dwindle, the mill attaining optimum effect at about 15-16 m./sec. wind velocity, thus making control unnecessary. Even if the wind is blowing almost a hurricane, the running of the mill will be steady, generator and transmission not being overloaded or strained.

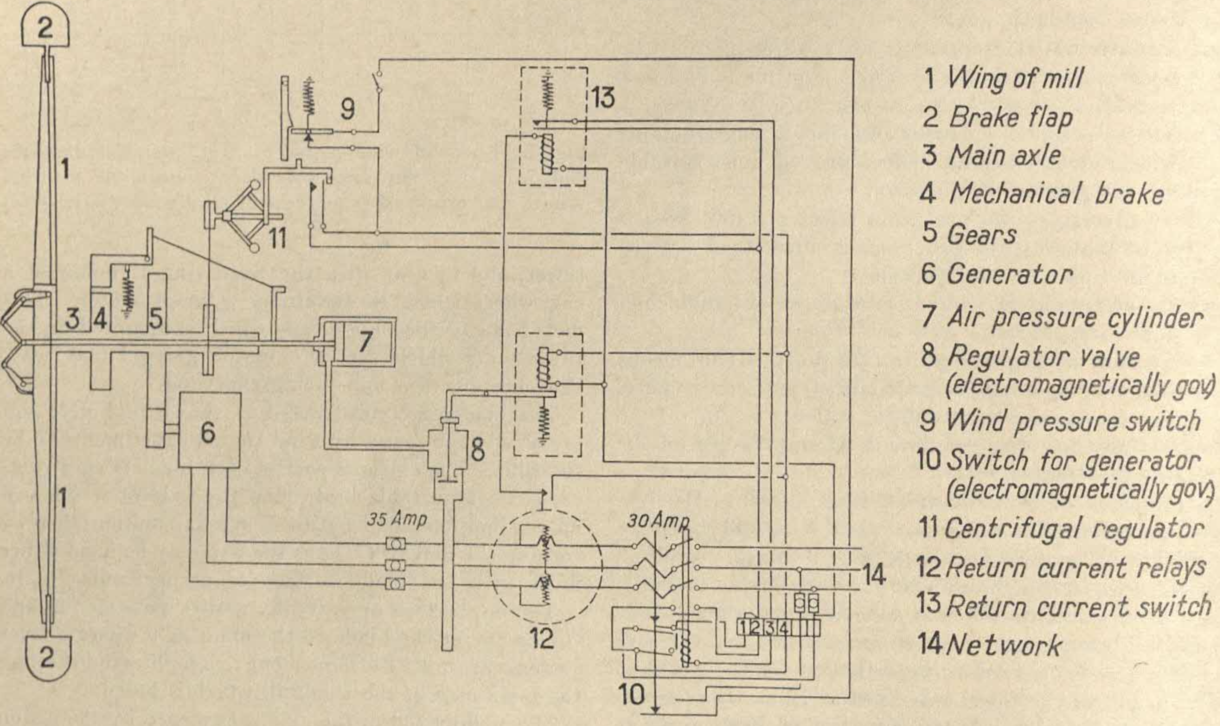

Fig. 4. SEAS' experimental mill.

The contrivances for adjusting the blades under these circumstances are only needed for braking the mill before stopping it and for stopping it altogether, and the brake flaps of the blade tips appeared to be sufficient for this purpose under any wind conditions. Thus it was found unnecessary to construct blades which would turn in their full lengthwise extension round their longitudinal axis. In other words it proved unnecessary to change the pitch or weathering of the whole blade. Blades can therefore be constructed so that the greater part of each blade is fixed and stayed by guys and struts, which is a cheaper and more reliable system of construction.

The initial and basic investigations and experiments being completed, the mill was made ready—about 1 May 1950—for continual running. The principle of the mill is shown schematically in Fig. 4 and the mill will function in the following way:

When the mill is switched on to the network (14) and is thus brought under tension, the magnetically governed valve (8) will let compressed air into the operating motor (7) and the brake flaps (2) will move into running position and be locked there by the air pressure of the operating motor. If the wind velocity is 4-5 m./sec. or more, the mill will start, and when the blade tip speed is 38 m./sec. the generator and the

A.C. network will synchronize. The centrifugal governor (11) will then couple the generator which will give off energy to the network as long as the wind velocity is 4-5 m./sec. or above. If the wind velocity dwindles to less than the 4-5 m./sec. the generator will receive energy from the network. The reverse current relay (12) will then function, switching off the connexion with the network. If the wind velocity again rises to 4-5 m./sec. the whole process is repeated.

When the connexion between the mill and the network is switched off, the magnetically governed valve (8) will let the compressed air out of the operating motor, the brake flaps (2) will move into braking position and the mechanical brake will lock the blades. In case the valve fails to function, the mill will increase its speed to above normal. The centrifugal power affecting the brake flaps will strongly increase, the air in the air pressure cylinder of the operating motor will be compressed by the piston which will move sufficiently for the brake flaps to go into braking position and prevent the mill from getting out of control.

When the mill had been running continually for three months, the extreme ends of the blades broke off at 6-7 m./sec. wind velocity. The main beam of the blade, of telescopic tube construction, consisted of two lengths of tube, two-thirds of the beam length being 4-in. tube, the extreme third being 2-in. tube. The breakage occurred in the immediate vicinity of the welding and showed plain signs of fatigue breakage. The mill having run, on the previous day, under full load and at 15-20 m./sec. wind velocity, it was rather peculiar that the breakage did not occur under these circumstances but took place on the following day at low wind.

A new set of blades was then constructed, the main beams now consisting of 4-in. tube in their full extension. In order to be able to construct a blade with the ideal profile, it was found expedient to flatten the extreme end of the tube.

The original set of blades was mounted on the lee side of the tower and had a leeward bend of about 15°, the centrifugal power affecting the blades thus counteracting to a certain extent the pressure of the wind on the blades. Experiments had shown that it was an advantage to run the mill at a lower speed than originally estimated. Hence the counteraction of the centrifugal power was considerably reduced and this circumstance was considered to be the cause of the breakage. So the new blades were fitted with stays against the wind pressure and mounted on the weather side of the tower as shown in Fig. Ic. For the purpose of switching off the operating current and stopping the mill in case abnormal vibrations developed, a vibration circuit-breaker was mounted in the cabin of the mill.

After another running spell of three months the mill again stopped, the vibration circuit-breaker having functioned. Investigation showed that a fissure had developed at the root of one of the blades, the blade having been bent in the direction of rotation. Obviously, then, the fatigue breakages of the blades could not be due to the pressure of the wind but to other causes. Computations showed that the effect on the blades of the force of gravity caused a strain on the material in the actual place of rupture amounting, in the first case, to 500 kg. per cm.^{2}, in the second case to 550 kg. per cm.^{2}. These strains alter with every revolution of the mill, working one way when the blade is on its way upwards and in the opposite direction when it is going downwards. Quite clearly, it was the effect of gravity upon the blades that produced the changing strains in the material which caused the breakages.

The blade set was again reconstructed and provided with two small streamline-profiled stay blades, mounted so as to support the main blades in the direction of rotation by means of side stays. The main blades, now, were supported with regard to wind pressure as well as to gravity, the effects of which increased when the blades rotated. After the reconstruction, gravity could cause no strains above 250 kg., while strains due to wind pressure were calculated so as not to exceed 700 kg. in any place, these strains being supposed to vary in one direction only.

Mounted with blades of the construction described above, the mill has been running continually day and night ever since April 1951—apart from short stops for experiments, for lubrication etc.—and no signs of blade defects have appeared.

For the purpose of measuring the effective power produced by the windmill a voltmeter and an ammeter as well as an automatically registering and a directly indicating wattmeter have been inserted in the generator circuit, kwh.-meter and k sin h-meter having been mounted in the operating room as well. At a distance of 80 m. from the mill and level with the mill main axle an electric anemometer has been mounted. This is connected with a directly indicating recorder in the operating room so that the wind velocity can be directly compared to the energy produced.

As opportunity offered for measuring the energy of the mill before fitting the stays, this was done, but no reduction of energy produced could be noticed after they were mounted. They are made of flat iron and are streamline profiled; they probably pull—to a certain extent—like the main blades.

In 1951 SEAS took over a D.C. power station on the Island of Bogø which is situated in a narrow sound between the islands of Zealand and Falstria. The prime mover of this station was a diesel engine and it had, in addition, an F. L. Smidth Aerogenerator with two 8.75 m. blades (propeller diameter 17.5 m.) and a swept area of 240 m.^{2}. The mill pulled a 35 kw. D.C. generator by gears, the transmission ratio being

1 : 18.2. The blades were wooden and were defective when the power station was taken over.

It was decided, as part of the experiments then going on, to reconstruct the Bogø mill so that it could produce A.C. for the SEAS network. The reconstruction was undertaken on the lines of the experience gathered from the Vester Egesborg mill. Bound by the transmission ratio of the existing gears and a blade tip speed of 38 m./sec. having proved most profitable, the propeller diameter required was 13 m. and the swept area 132 m.^{2} or just over half the original swept area of the mill. The new experimental mill was provided with a 45 kw. asynchronous generator with automatic contrivances on the lines of the Vester Egesborg mill, with the exception that it was fitted, in addition, with a winch—driven by an electromotor—which loads a heavy spiral spring that keeps the brake flaps in position. This last contrivance performs the same function as the Vester Egesborg mill operating motor which operates by compressed air. Both contrivances have answered their purpose. The Bogø mill was fitted three blades of 750 mm. width along their whole length. The blades are supported against axial pressure by means of stays from a frame mounted on the main axle hub. The blades are also interconnected by stays so that the effect of gravity on the blade moving upwards is counteracted by the same effect on the blade moving downwards.

The Bogø mill has been running since October 1952 without any notable defects appearing.

EFFICIENCY AND ENERGY PRODUCTION OF THE EXPERIMENTAL MILL

For the purpose of determining the efficiency of the experimental mills, registering wattmeters and directly indicating precision wattmeters have been used, ordinary kwh.-meters having been employed for the measuring of energy produced.

Furthermore, the *k* sin *h* consumption of the generators has been measured in the usual way.

For determination of the velocity of the wind automatically registering and directly indicating electrical anemometers have been used. They are connected with recorders mounted beside the wattmeters in the operating rooms, while the anemometers themselves have been placed at distances of 80 m. from the experimental mills and at a height level with their main axles.

Wind velocity at a mill and at its anemometer at any given moment often being unequal, the efficiency has to be determined as averages for periods of steady wind. For both of the mills efficiency was determined at westerly sea winds which—during short periods of a few minutes—were found to be practically without variation of velocity. Hence inaccuracies deriving from the fact that the wind velocity, when computations are made, is involved to the third power, could be practically eliminated. The efficiency of the mills has been determined at different blade tip speeds and some results are shown in Fig. 5, curve 1 being the efficiency at 38 m./sec. blade tip speed of the Vester Egesborg mill, curves 2 and 3 being that of the Bogø mill at 38 and 34.3 m./sec. blade tip velocity respectively. On Fig. 6 are shown the characteristics of the mills and from these it will be seen that they alter considerably when the blade tip speeds alter. From this it appears that the adjustment of a mill to the local wind régime is a matter of significance. Hence it is of great importance to know the wind velocities most frequently occurring in the course of the year on the site of the mill, also to fix the number of revolutions per minute and the blade tip speed so as to place the greatest possible number of wind hours within the range of the greatest values attained by the efficiency curve of the mills.

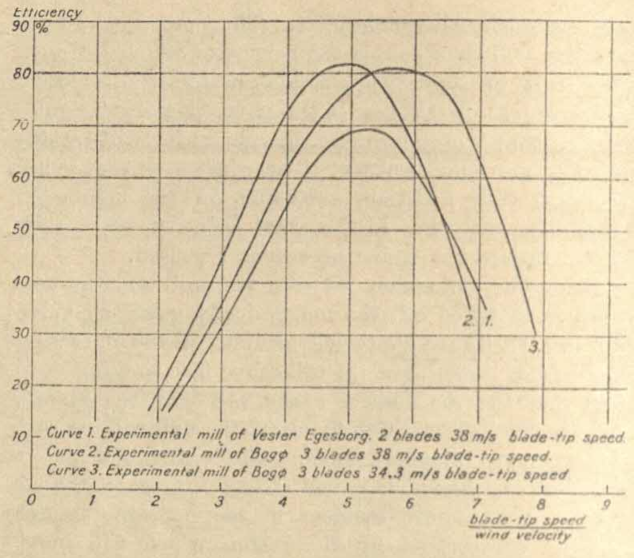

Fig. 5. Effects, expressed in per cent of total wind effect, of experimental mills with different blade tip speeds.

If, for instance, the prevailing wind velocity in a certain place is between 5 and 8 m./sec., a blade tip speed of 34.3 m./sec. will render a greater annual amount of energy than a blade tip speed of 38 m./sec. this last mentioned blade tip speed being, perhaps, more profitable in a place where the prevailing velocity is 7-10 m./sec.

In order to adjust a wind power plant in the most advantageous way, it is therefore expedient not only to measure the annual output (in kwh.) but also to determine the number of hours of average wind velocity and to note the character of the wind, thus getting an impression of its turbulence on the site in question.

The curves of Fig. 10 show, besides, the advantages or otherwise of using three blades instead of two blades on a mill. At a blade tip speed six times the velocity of the wind, two blades will render as much as three; if blade tip speed increases to above the speed mentioned, two blades will render more than three and if the blade tip speed dwindles to less than six times the wind velocity, three blades will render more than two. If the ratio is three to four instead of six, a 3-blade mill will render 25-35 per cent more than a 2-blade mill.

The results enumerated above are valid only for such mills as are fitted with blades of the construction already described.

If blades of different profile and twisting are used, the characteristic of the mill will be different, as well.

The annual amounts of energy produced by the experimental mills are shown in Table 1 which shows the monthly output as well as the amounts of energy computed according to average wind velocity per hour measured. The table shows, also, the results of direct energy measuring by the instrument of Electricité de France.

The Vester Egesborg experimental mill appears to have attained an output of 525 kwh. per m.^{2} swept area or 39 per cent of the wind energy measured by anemometer. The corresponding figures of the Bogø mill are 660 and 53, calculated on the basis of average wind velocity per hour.

But for the necessity of providing the Bogø mill with adjustment contrivances—on account of the dimensions of axles and gears which were not suited for the strain involved by the optimal capacity of the mill—it would have been able to render more energy. This circumstance has reduced the production of the Bog mill by an amount of energy estimated at 10 per cent.

After the Bogø mill had been reconstructed for A.C. production to be supplied to a network capable of consuming the whole output, it rendered four to five times the energy rendered when, formerly, it produced D.C. for a network which could not take delivery of the full production possible, on account of circumstances pertaining to tension and to the difficulties of storage.

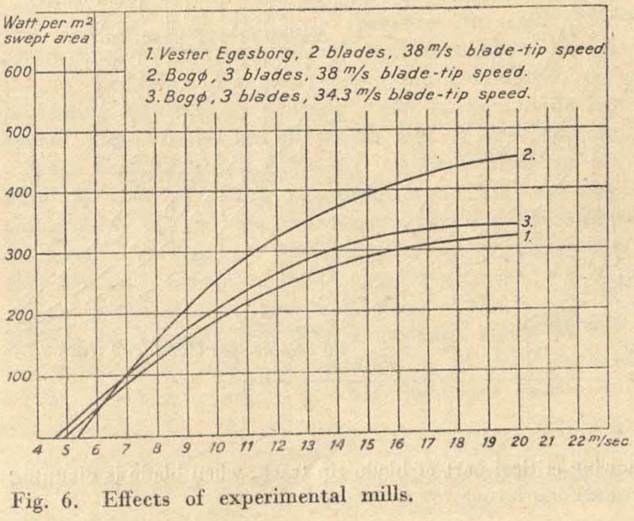

Fig. 6. Effects of experimental mills.

The Bogø mill has proved it possible to transform 50-60 per cent of the theoretical average wind energy into 3-phase alternating current.

This can be done by using a synchronous or an asynchronous generator, the latter, being the simpler system permitting as it does control of night-time tension by the means already existing, and supplying energy of the same voltage as that of the network from which it is excited. For excitation it will use a number of *k* sin *h* from the network very nearly corresponding to the number of kwh. produced for the network.

Investigations must be made in each separate locality in order to ascertain whether in the case in hand it will be expedient to insert a suitable condenser for producing the blind effect for exciting the generator or whether to produce *k* sin *h* to the necessary extent elsewhere.

DETERMINATION OF THE EFFECT OF WIND UPON WIND MOTORS

The calculation, construction and erection of a wind power plant in a manner that ensures the necessary safety from breakage and without the use of superfluous quantities of material, demand a thorough knowledge of the forces to which the several parts of the construction are exposed.

Wind power plants being placed, as a matter of course, where the greatest possible wind power can be obtained, it is necessary to reckon with the maximal wind pressures normally involved when building lighthouses, bridges and similar constructions which are exposed to great wind pressure. This holds good as far as the stationary parts of the wind power plant are concerned, whereas other conditions prevail regarding the rotating blades.

If a rotor blade of streamlined profile is moving perpendicularly to the direction of the wind, the effect of the wind upon the blade will be roughly as shown in Fig. 7, vector 1 showing the wind velocity, vector 2 showing the blade tip speed, which may be, for example, six times the velocity of the wind. The wind resultant acting upon the blade will then be of a magnitude and direction as shown by vector 3. The blade is thus exposed to a power which finds expression in an axial pressure shown by vector *a* and, further, in a working pressure in the plane of the swept area shown by vector *b*; the amount of the latter pressure can be calculated on the basis of the energy produced by the mill according to measurings. The amount of the axial pressure will depend upon the design of the blade and its speed in relation to the velocity of the wind. The axial pressure per unit blade area will vary from a maximum at the blade tip to a minimum towards the swept area centre, where the active part of the blade ends.

As mentioned in the preceding section on construction of experimental mills, the SEAS experimental mill at Vester Egesborg was so constructed that the axial pressure could be measured and registered. This has been done at the blade tip speed which was found to be most suitable under the circumstances, namely 38 m./sec. and at wind velocities up to about 25 m./sec.

The results are shown in Fig. 8, curve 1 indicating axial pressure per m.^{2} swept area up to 30 m./sec. wind velocity, while curve 2 represents the total wind pressure upon tower and blades at wind velocities not exceeding 50 m./sec. and with the mill at a standstill, the mill being supposed to stop automatically at 30 m./sec. wind velocity. In Denmark wind velocity of 30 m./sec. occurs but seldom, but velocities of up to 50 m./sec. have to be reckoned with, though very rarely. Curve 1 is the resulting average of many measurings of, partly, the axial pressure and, partly, the wind velocity measured at a distance of 80 m. from the mill, the maximum readings within 10-minute periods being compared.

The results shown in curve 1 of Fig. 8 apply only to a 2-blade mill, which is adjusted like the experimental mill. Where a 3-blade mill is concerned the axial pressure will increase by $\frac{3}{2}$ and at increased blade tip speed there will also be an increase of the axial pressure.

As the blades, when rotating, are not usually working in homogeneous wind, torsion will occur in the blade system, especially vertically, wind velocity increasing with increasing height above ground. Hence the axial pressure will vary with a frequency equal to the number of blades multiplied by the number of revolutions. It is therefore very important to prevent the oscillations of the tower from coinciding with the frequency of the axial pressure, as otherwise resonance will develop, which may have detrimental effects on the mill tower.

Owing to the turbulence of the wind, horizontal torsion, also, will occur, measurings at 12 m. height having proved differences in wind velocity of about 30 per cent to appear at a distance (horizontally) of 22 m. between two observation masts. The torsional

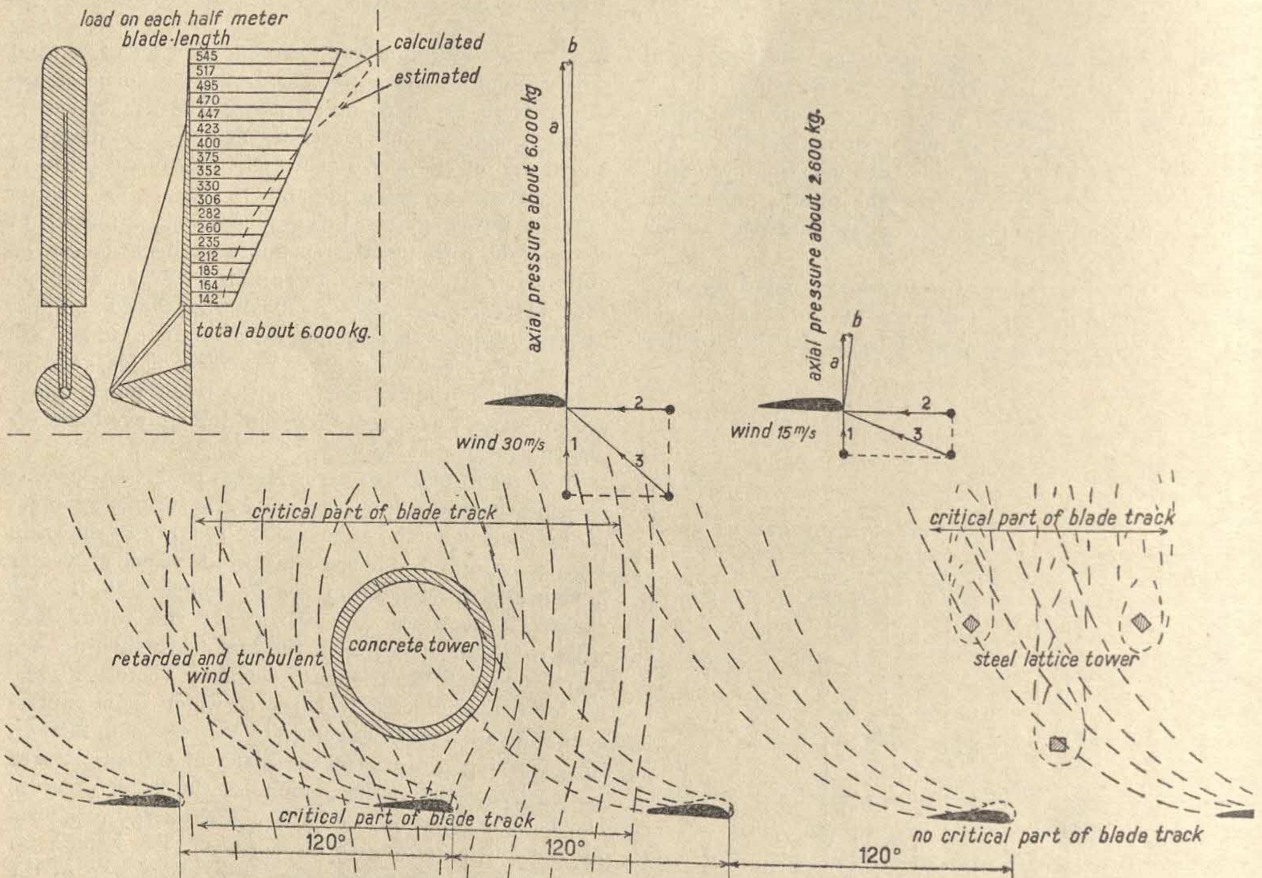
load on each half meter blade-length
545
517
495
470
447
423
400
375
352
330
306
282
260
235
212
185
164
142
calculated
estimated
total about 6.000 kg.
axial pressure about 6.000 kg
a
b
2
1
3
wind 30 m/s
axial pressure about 2.600 kg.
a
b
2
1
3
wind 15 m/s
critical part of blade track
concrete tower
retarded and turbulent wind
critical part of blade track
critical part of blade track
steel lattice tower
120°
120°
120°
no critical part of blade track
one revolution

Fig. 7. Schematic account of pressure on a 12-metre blade, showing critical part of blade tip track, when blade is mounted on concrete tower (i.e. tower offering unbroken surface to the wind) and lattice tower, respectively.

effects are to some extent counteracted by the gyrostatic effect of the rotating blades but it will undoubtedly be necessary to reckon with the pressure on the tower being increased by about 20 per cent due to torsion.

If closed towers (i.e. towers offering an unbroken surface to the wind) are used, oscillations will arise and, besides, the pressure on the blades, when they pass the area of wind influenced by the tower, will be puffy.

The closed tower will cause the wind to stow on the weather side of it and alter the direction of the wind on both sides of it. The effects of this are discernible within a distance from the tower of more than its diameter and may cause an alteration of the force and direction of the wind pressure on the blade for the fraction of a second during which the blade passes the area in question.

Thus the blade is exposed to a treatment which is nearly comparable to blows from a club and which will have a most harmful effect on the blade material, causing fatigue phenomena to appear.

This fact was well known to the old time millwrights, who made mill sails covered with canvas. To prevent the canvas from wearing out too soon, they had to give the extreme end of the sail a special shape which reduced its effect and its capability of starting at low wind. In modern wind power plants with concrete towers, breakage of the blades has occurred due to fatigue in the material, while similar phenomena have not appeared in blades which are mounted on a lattice tower which does not cause eddies or deflections of the wind in the area passed by the blade on the weather side of the tower.

On the lee side of a lattice tower and particularly on the lee side of a concrete tower turbulent and retarded wind will be found. When using mills of a construction where the blades rotate behind (i.e. to the leeward of) the tower, jerky and therefore highly detrimental loads on tower and blades have to be reckoned with.

On a basis of the axial pressure as measured at the experimental mill, the axial pressure on each half metre blade length of a 3-blade mill with 12 m. blades (24 m. propeller diameter) has been calculated, the mill being adjusted for running at 38 m./sec. blade tip speed. The results are shown in Fig. 8 and indicate a total load of about 6,000 kg. on each blade or an axial pressure of 18,000 kg. altogether. This calculation plainly shows how disastrous would be the consequences of momentary variations of force and direction of this pressure on blades passing a closed tower, which causes stowing and deflections of the wind. A further 20 per cent load with a torsional effect on the tower has to be reckoned with, owing to the rotation of the blades in turbulent and heterogeneous wind over the whole of the swept area.

Characteristic of the axial pressure is the fact that it will vary between a minimum and a maximum in unison with the variations of the wind velocity.

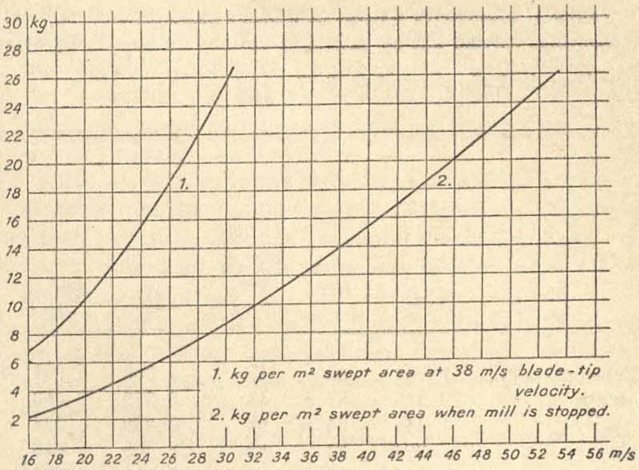

Fig. 8. Axial pressure experimental mill at Vester Egesborg.

Owing to the force of gravity strains will develop in the material of the blade when it rotates in the vertical plane. Dduring the upward movement of the blade, gravity minus blade torque will work in one direction and during its downward movement on the opposite side of the swept area, gravity plus blade torque will work in the opposite direction.

For the construction of blades, wood—almost exclusively—was formerly used. Wood has the advantage of being fairly resistant to plus and minus forces so that it will not easily suffer fatigue breakage. It is, furthermore, fairly easy to give wooden blades the right shape. Most sorts of wood, however, having a tendency to warp, the shape and the twist of the blade may alter, thus reducing its aerodynamic qualities and its efficiency. In addition, the durability of wooden blades is rather limited. The pressure on a correctly designed modern blade is greater, by many times, than the pressure on a old-fashioned mill sail. For this reason it is difficult to make the modern blades out of wood and yet obtain the necessary strength. Already 50 years ago the use of steel for the bearing parts of the mill sails or blades was introduced, the sails or blades being mutually stayed by guys to eliminate the harmful influence of gravity. The steel blades were further supported by stays to some protruding part of the weather end of the mill main axle. These blade systems have proved to be most durable and in many cases have been working for 30-40 years without any defects developing in the blades.

The bearing parts of the SEAS experimental mill are made of steel and calculated so that positive and negative effects of gravity will not cause tensions in the steel exceeding 200-300 kg. per cm.^{2}, while a tension of 700-1,000 kg. per cm.^{2} due to maximal effects, though rare, of the wind pressure has been reckoned with.

When designing steel blades so as not to exceed the tensions mentioned, it appears to be practically impos-

TABLE 1. Electricity output of SEAS's experimental mills at Vester Egesborg and on the Island of Bogø; also wind effect measurings carried out by means of various automatically registering anemometers; the effect being computed according to the formula $\text{kwh. per m.}^2 = 0.37 \left(\frac{V}{10}\right)^3$

	Vester Egesborg			*Bogø*					*Wind effect measurings kwh. per m.²*				
	Output		*Usable energy*	*Output*				*Usable energy*					
	kwh.	*kwh. per m.²*	*per cent*	*kwh.*	*kwh. wasted*	*kwh. total*	*per m.²*	*per cent*	*1*	*2*	*3*	*4*	*5*
February 1953	2 732	65	45	5 333	6 001	11 334	85.8	47.6	236	144			180
March	2 415	57.5	53	6 570	2 463	9 033	68.3	52.5	130	109			130
April	1 449	34.5	69	4 230	774	5 004	37.9	52.6	83	50			72
May	994	23.7	43	4 405	419	4 824	36.5	59	77	55	59		62
June	1 502	35.8	39	2 110	2 035	4 145	31.5	73	57	91	93		43
July	2 145	51	37	4 400	745	5 145	39	57.3	80	137	141	134	68
August	2 414	57.4	39	7 470	315	7 785	59	60.2	99	148	161	142	98
September	1 838	43.8	34.5	7 000		7 000	53	43	105	127	146	130	123
October	1 088	26	29.8	5 000		5 000	38	57.5	70	87	63	51	66
November	2 280	54.3	30	10 600		10 600	80.3	45	172	180	159	142	179
December	886	21	45.7	5 600		5 600	42.5	72	133	46	83	28	59
January 1954	2 304	55	33	11 700		11 700	88.6	51	290	168	219	164	173
Total for the whole year	22 047	525	39	74 418	12 752	87 170	660	53	1 532	1 342			1 253
Total July 1953-January 1954	12 955			51 770	1 060				949	893	972	791	766

1. Readings supplied by the Meteorological Institute from measurings at the Kastrup Aerodrome (Island of Amager, near Copenhagen).
2. Registered at Vester Egesborg by means of SEAS anemometer.
3. Registered at Vester Egesborg by means of Électricité de France anemometer.
4. Registered at Vester Egesborg by means of Electrical Research Association anemometer.
5. Registered on Island of Bogø by means of SEAS anemometer.

sible to construct the blades without support from guys or stays.

If the stays are made of flats which have been shaped so as to have the same profile as the blades, the stays will cause no reduction of the effect of the blades and even give impetus to the blade system. It is essential, however, that the stays are non-breakable and carefully fixed at both ends, because a broken stay may cause the whole blade system to collapse.

CONSTRUCTION OF FUTURE WIND POWER PLANTS

In the course of time many different proposals for the design of windmills have appeared, but the vertically rotating windmill known of old is, practically, the only one that has been used and I am of the opinion that this system will still prevail, because it renders a fairly considerable effect in comparison to the amount of materials necessary for its construction.

By means of the new streamline-sectioned blades it has proved feasible to extract up to 80-90 per cent of the theoretical wind energy within the swept area when the blade tip speed was the one most suitable to the wind velocity, and on an average it is possible to transform 50-60 per cent of the annual wind energy within the swept area into 3-phase current.

In consideration of these facts, the following designs of wind power plants for the production of 3-phase alternating current are proposed.

A propeller diameter of 24 m. has been chosen. The reason for this choice is the question of transmission between blades and generator. Wind conditions in Denmark are such as to make a blade tip speed of about 40 m./sec. the most profitable one. The revolutions per minute will then be about 30 and the ratio of transmission to an 8-polar generator will be 1 : 25, which can be achieved by two sets of sprocket wheels or gear wheels without the gear wheel strain becoming excessive. If a greater propeller diameter than 24 m. is chosen, the revolutions per minute of the blades will be reduced correspondingly, the ratio of transmission to the generator will increase and the strain on the transmission gears will necessitate the use of disproportionately expensive gears.

If wind power plants of great capacity are wanted it will be necessary, in my opinion, to make batteries composed of many units or to construct large sustaining frameworks on which a suitable number of rotors can be mounted.

As I see it, conditions pertaining to the construction of wind power plants are about the same as those applying to the construction of diesel engines. If the latter are wanted in great units, the use of multi-cylinder high-speed engines has proved more profitable than the construction of big single-cylinder slow-speed engines.

A wind power plant with 24 m. propeller diameter and working at 40 m./sec. blade tip speed will have a maximum capacity of about 200 kw. This may seem a trifle in comparison with the production of the big main power stations which is often 200-300 times greater. It should not be overlooked, however, that the thermal power works are at a disadvantage in being unable to utilize coal economically and to produce cheap electricity in small quantities. If they had been able to do so, smooth and uninterrupted running of the power supply would be less vulnerable and an increase of product could be brought about gradually. Actually, wind power plants are at a not inconsiderable advantage in being able to supply cheap electricity from small units situated in suitable places within the area of distribution, most of the power supplied being utilized by small size machinery and motors spread over an extended area.

These conditions prevail, especially, in the countryside. Since the supply of the countryside is in most places interconnected with that of the neighbouring towns, it should be quite possible to transmit the wind power collected by the small country plants to the town consumers.

Time will show how wind power plants of the future will look when as much technical skill has been applied to designing them and as much practical experience has been gained regarding their construction as is the case where thermal power plants are concerned. So far, wind power plants have been rather neglected, but wind power plants will undoubtedly be able to satisfy a large part of the demand if modern technique and science are brought to bear on the problem.

To obtain a general estimate of wind power plant building costs, I have made a summary and an advance calculation of various types of wind power plants which in my opinion might be adequate. There are two types in particular on which I have focused my attention—a 1-rotor type which is merely an adaptation of the old type of Dutch windmill, and a new 2-rotor type which is able to utilize the increased wind energy to be found at greater height above the ground.

The first type has a tower, the lower part of which is made of reinforced concrete up to a certain level, beyond which it consists of steel lattice so as not to affect the blades. The lower part serves as foundation and ballast, anchoring the tower to the ground. In the lower part of the tower a transformer room and operating room can be arranged. A height of 35 m. would probably be advantageous.

The second proposal aims at mounting two blade systems jointly on one frame, supported by stays, which will turn inside a collar to which the stays are fixed, according to the direction of the wind. The height of the frame is to be 55-60 m.

The calculation is based on present Danish standard prices for building materials, machinery and electrical equipment known from experience to be required for similar constructions.

The estimated costs in Danish crowns[1] will be approximately:

	Design I	*Design II*
Blades	25 000	50 000
Transmission and cabin	28 000	56 000
Electrical equipment	23 500	47 000
Transformer with appurtenances	17 500	22 000
Tower, mounting of tower, foundation and transformer-house	100 000	130 000
Site, road, etc.	6 000	12 000
	200 000	317 000
Maximum effect	200 kw.	400 kw.
Price per kw.	1,000	800

ECONOMICS OF FUTURE WIND PO PLANTS

Beyond everything else, the local wind régime will be the decisive factor in the economics of a wind power plant.

In Denmark the greatest amount of wind energy is to be found along flat western stretches of seashore. The wind there is steady and powerful even at a fairly low height. Fig. 9 shows the annual wind energy per m.^{2} measured at a height of 12 m. above ground level and the increase according to height has been computed in accordance with similar measurings undertaken elsewhere in Denmark by the author and in France by Electricité de France.

According to working results attained by the Bogø mill, a gain of 53 per cent of the existing annual wind energy can be reckoned upon, transferred as 3-phase alternating current into an existing network.

Hence the two designs of wind power plants described in the previous section should be able to render the

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[1] 1 Danish crown equals about U.S. $0.14.

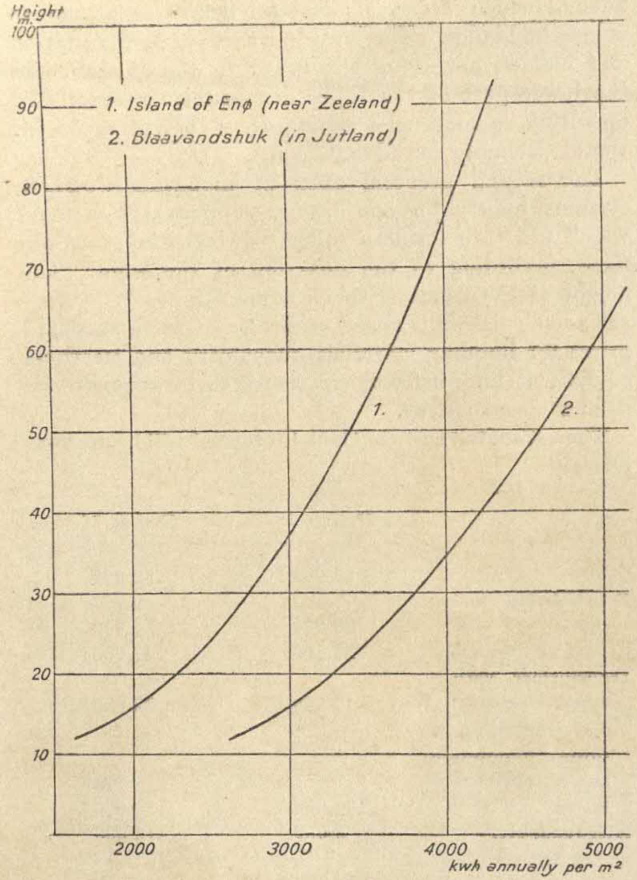

Fig. 9. Wind energy per m.^{2} in relation to height above ground.

following annual outputs on the western coasts of Jutland and Zealand respectively:

	Design No. 1		Design No. 2	
	kwh.	*Annual working periods*	*kwh.*	*Annual working periods*
		hrs.		hrs.
Zealand	700 000	3 500	1 540 000	3 850
Jutland	961 000	3 800	1 971 000	4 900

Estimates I have made indicate that batteries of wind power plants can be run at an annual cost of about 10 per cent of the building cost for interest, amortisation, upkeep and maintenance.

Thus the cost of production per kwh. will be:[1]

	Design I	*Design II*
	øre	øre
Western coast of Zealand	2.85	2.05
Western coast of Jutland	2.07	1.62

Judging by these figures it will be a material advantage to use Design II instead of Design I and these provisional estimates show that it will be expedient to aim at constructing wind power plants consisting of high frames mounted with a greater or lesser number of rotors or blade sets.

Electricity production by the most modern thermal power plants in Denmark at present costs about 3 øre per kwh. As coal prices fluctuate to a very great extent and are today rather low in comparison to the average coal price of the last five years, I believe that the building of wind power plants in order to save coal is sound business.

As wind power, however, is not always available—which to a certain extent applies also to hydraulic power—the full production cannot infallibly be relied upon. However, if several wind power plants are supplying electricity to a widely extended network, it is fairly safe to count upon a certain amount of wind energy being available somewhere in the extensive network, at least in western Europe where absolutely calm weather over an extended area is very rare indeed.

I should, therefore, be inclined to think that, where networks covering whole countries are concerned, at least 25 per cent of the wind power plant production will always be available.

When judging the value of hydraulic power plants, the relation between building costs and annual production is often made out as a fraction. This procedure provides a sound basis for judging the value of a wind power plant.

In connexion with the hydraulic power plants built or extended during the last few years, this method of computing has given us some interesting information, as shown by the following example:

	Building cost (crowns) *annual production (kwh.)*
Hydraulic power	
Sweden	0.270
South European Alps area	0.500
Faeroe Islands	0.200
Iceland	0.300
Wind power	
Design I, Zealand	0.285
Design II, Zealand	0.205
Design I, Jutland	0.207
Design II, Jutland	0.162

Thus, wind power will cost about the same as hydraulic power in Scandinavia, but is considerably cheaper than hydraulic power in southern Europe. The main reason for this is that the areas in northern Scandinavia, which are flooded by damming up the water, are very cheap because unsuitable for agriculture. In southern

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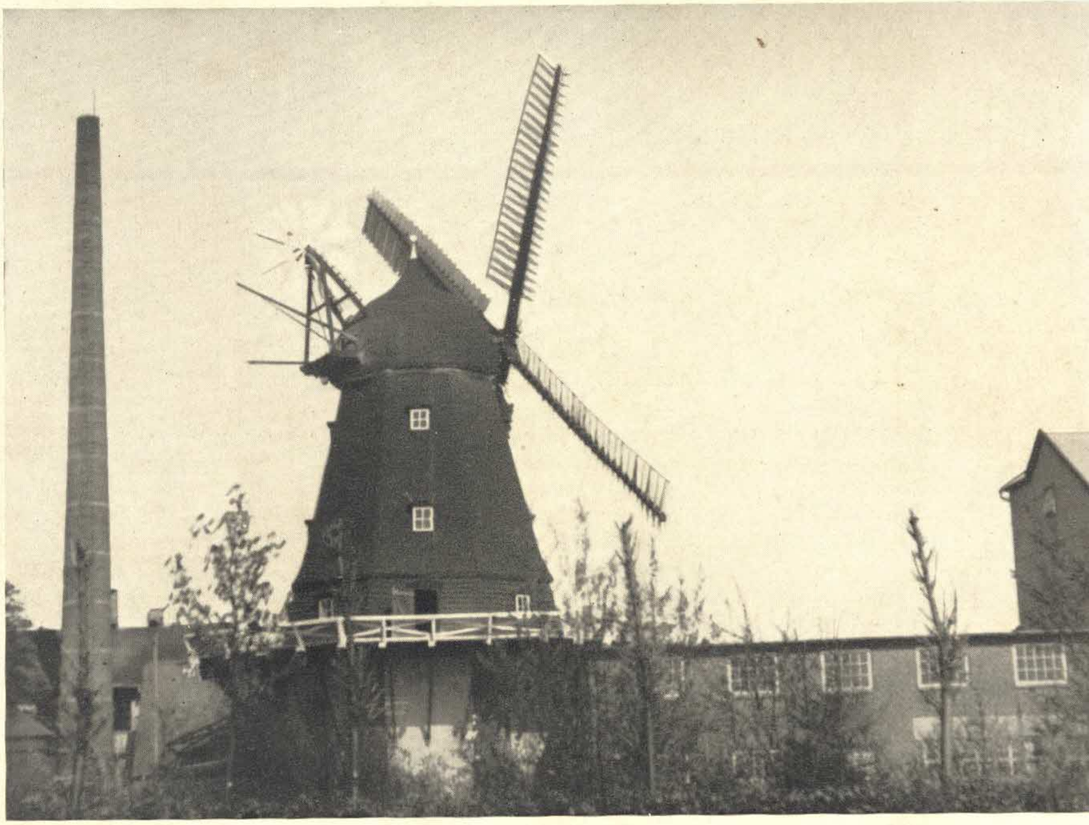
[1] 1 crown = 100 øre.

I*a*

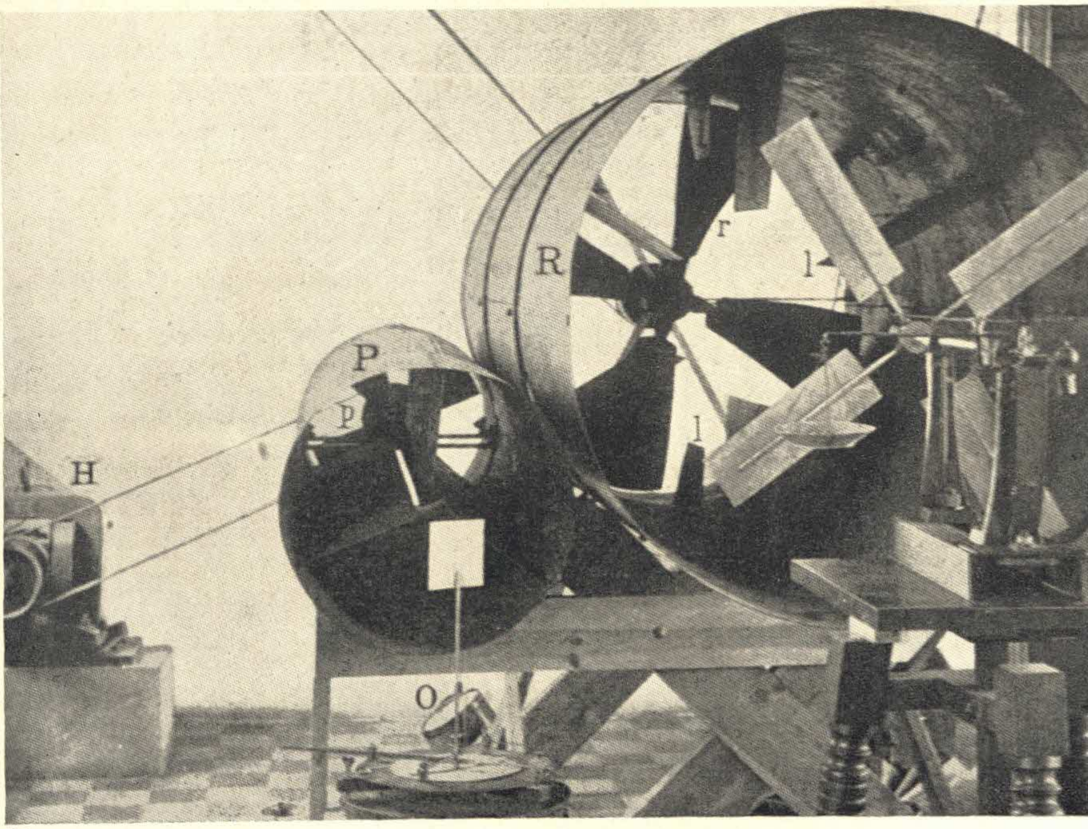


Industrial mill in Denmark.

Moulin à vent danois à usage industriel.

Molino industrial en Dinamarca.

(Cf. p. 56.)



I*b*

Wind tunnel of the Askov experimental mill, probably the first wind tunnel in the world ; made about 1895.

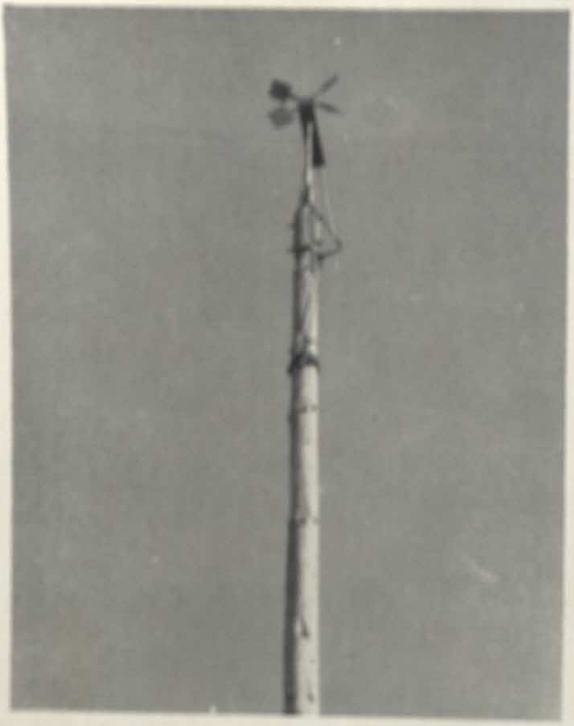
Soufflerie de l'installation expérimentale d'Askov. Construite vers 1895, c'est sans doute la plus ancienne du monde.

Túnel aerodinámico del molino experimental de Askov, probablemente el primer túnel aerodinámico del mundo ; construído hacia el año 1895.

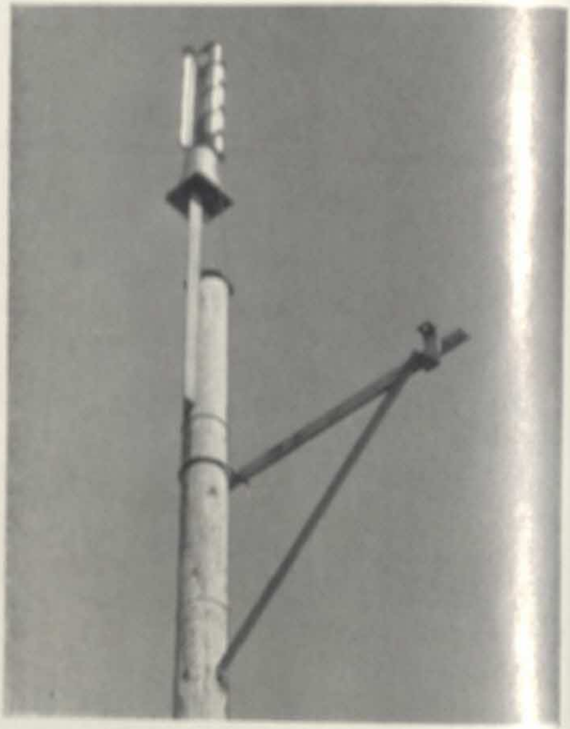
(Cf. p. 56.)

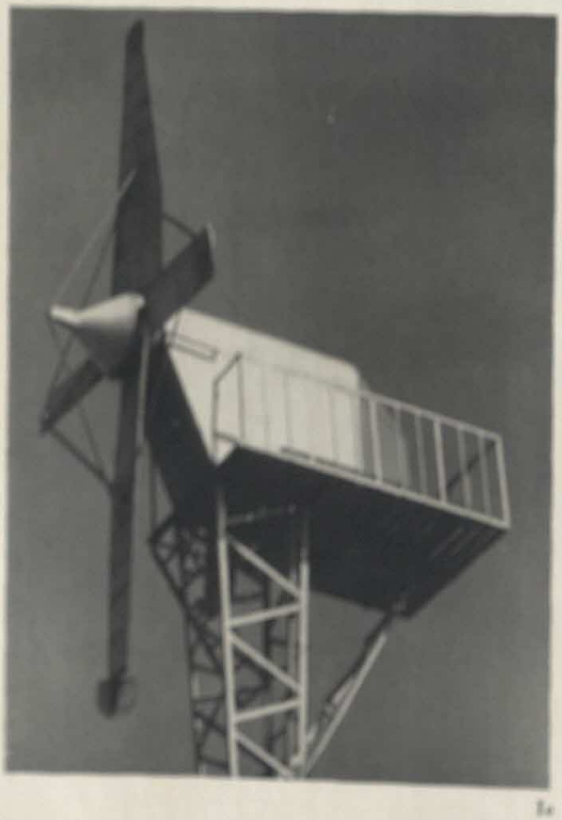
Photos/Fotos: Juul.

1c



1d





1e

SEAS' automatically registering anemometer.

Anémomètre enregistreur automatique SEAS.

Anemómetro SEAS de registro automático.

(Cf. p. 60.)

Wind energy meter, French make.

Anémomètre de fabrication française.

Contador de energía eólica, de construcción francesa.

(Cf. p. 60.)

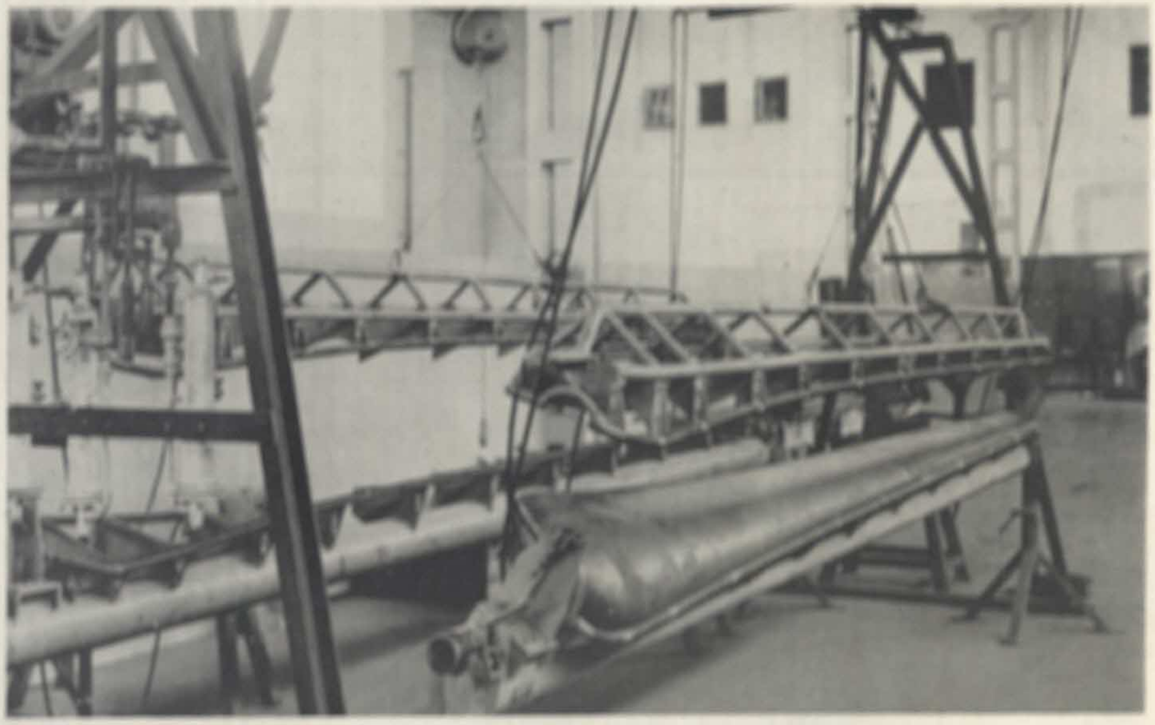
Experimental mill at Vester Egesborg, Denmark: braking adjustment.

Dispositif de freinage de l'éolienne expérimentale de Vester Egesborg (Danemark).

Molino experimental de Vester Egesborg (Dinamarca): el mecanismo de freno.

(Cf. p. 65.)

Photos; Fotos : Juul

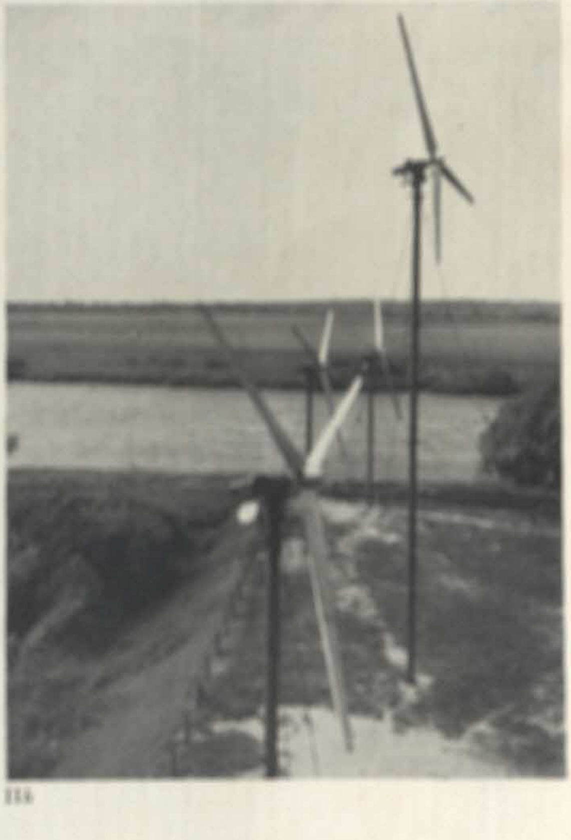


Water-cooled welding apparatus for assembling Allgaier steel plate shell-shaped propellers.

Dispositif de soudure à refroidissement par eau pour l'assemblage des pales creuses en acier des hélices Allgaier.

Aparato de soldadura refrigerado por agua para el montaje de hélices de acero en forma de pala, de la casa Allgaier.

(Cf. p. 41.)



Part of the Allgaier 3-phase current wind power plants Model WE 10, erected on 10 and 13 m. high tubular steel towers in parallel operation at the pump station Neuenfelder Hammerich with a single pump.

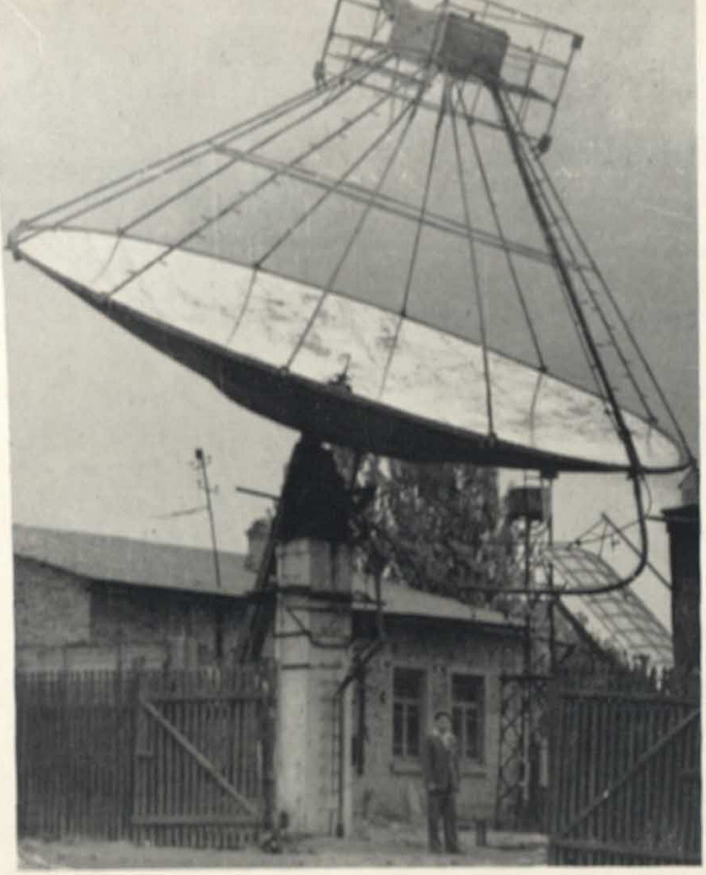
Vue partielle des aéro-générateurs de courant triphasé modèle WE 10, montés sur mât tubulaire en acier de 10 et 13 mètres, fonctionnant en parallèle sur une seule pompe à la station de pompage de Neuenfelder Hammerich.

Parte del grupo electrógeno trifásico Allgaier modelo WE 10, montado sobre torres de acero tubular de 10 y 13 metros de altura, que funcionan en paralelo en la estación Neuenfelder Hammerich con una sola bomba.

(Cf. p. 41.)

Photos Fotos : Allgaierwerke, Uhingen.

IIa



A solar steam boiler with an 80 m.² parabo-loidal mirror. Capacity: 60 kg. of 7-atmospher steam per hour. Tashkent.

Chaudière solaire équipée d'un miroir parabo-loïdal de 80 m². Débit : 60 kg de vapeur à l'heur sous 7 atmosphères. Tachkent.

Caldera solar equipada con un espejo parabo lóidico de 80 m². Capacidad: 60 kg de vapor 7 atmósferas por hora. Taskent.

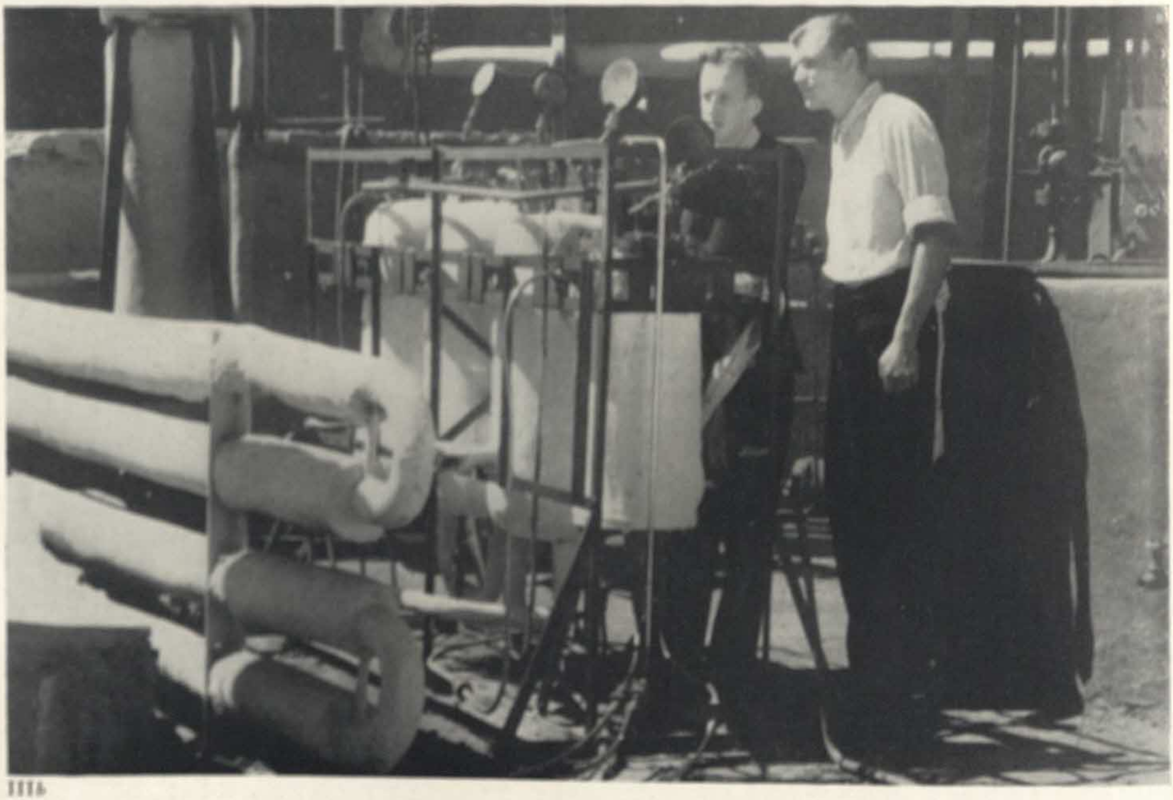
(Cf. p. 154.)

Three-stage distiller working with a solar steam boiler. Capacity: 1,000 kg. of distilled water per day.

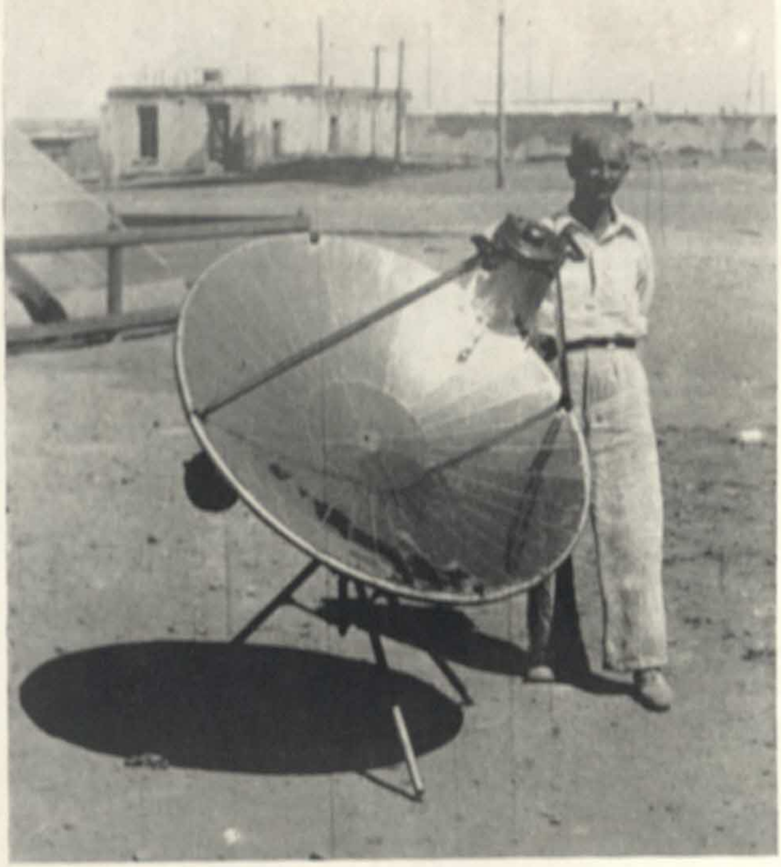
Appareil de distillation fractionnée à trois étages alimenté par une chaudière solaire. Débit 1,000 kg d'eau distillée par jour.

Destilador de tres fases funcionando con una caldera solar. Capacidad: 1,000 kg de agua destilada por día.

(Cf. p. 155.)



IIIb



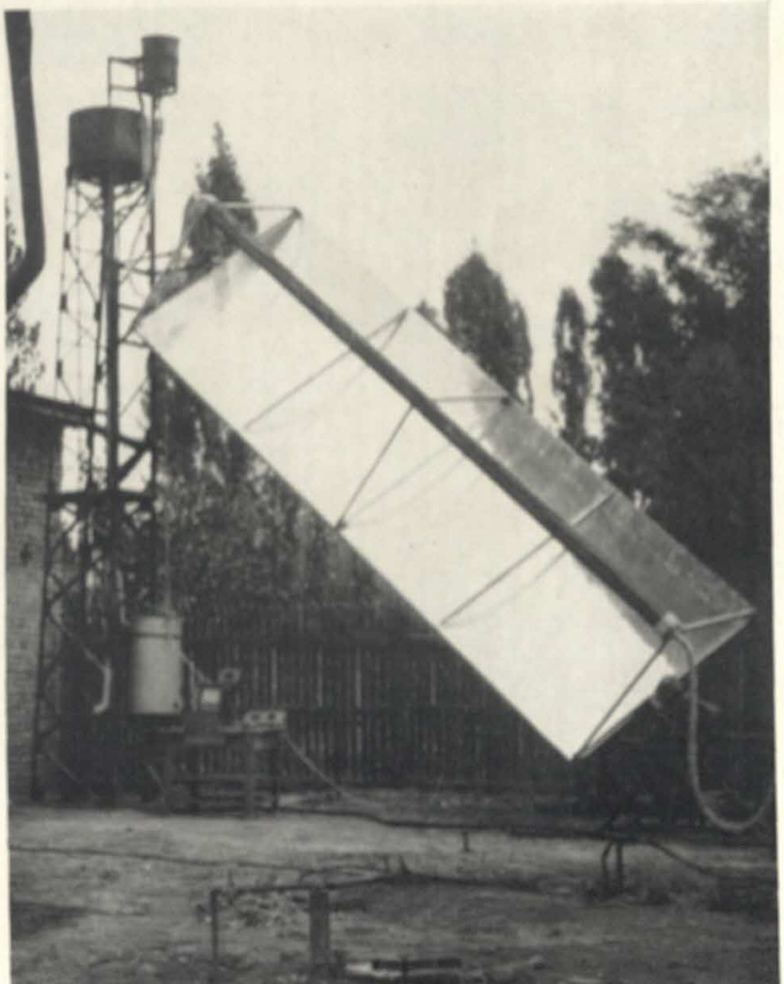
III*c*

A solar kitchen for a family of 3 to 5 persons. It has an inaccurate aluminium 1.2 m.^{2} paraboloidal mirror. On a sunny day it does the work of a 600 watt electric stove.

« Cuisinière solaire » pour famille de 3 à 5 personnes. Elle est équipée d'un miroir pseudo-paraboloïdal en aluminium de 1,2 m^2. Par temps ensoleillé, elle rend les mêmes services qu'une cuisinière électrique de 600 watts.

Cocina solar para una familia de 3 a 5 personas. Tiene un espejo seudoparaboloide de 1,20 m^2. En un día soleado produce el calor de una cocina eléctrica de 600 vatios.

(Cf. p. 155.)



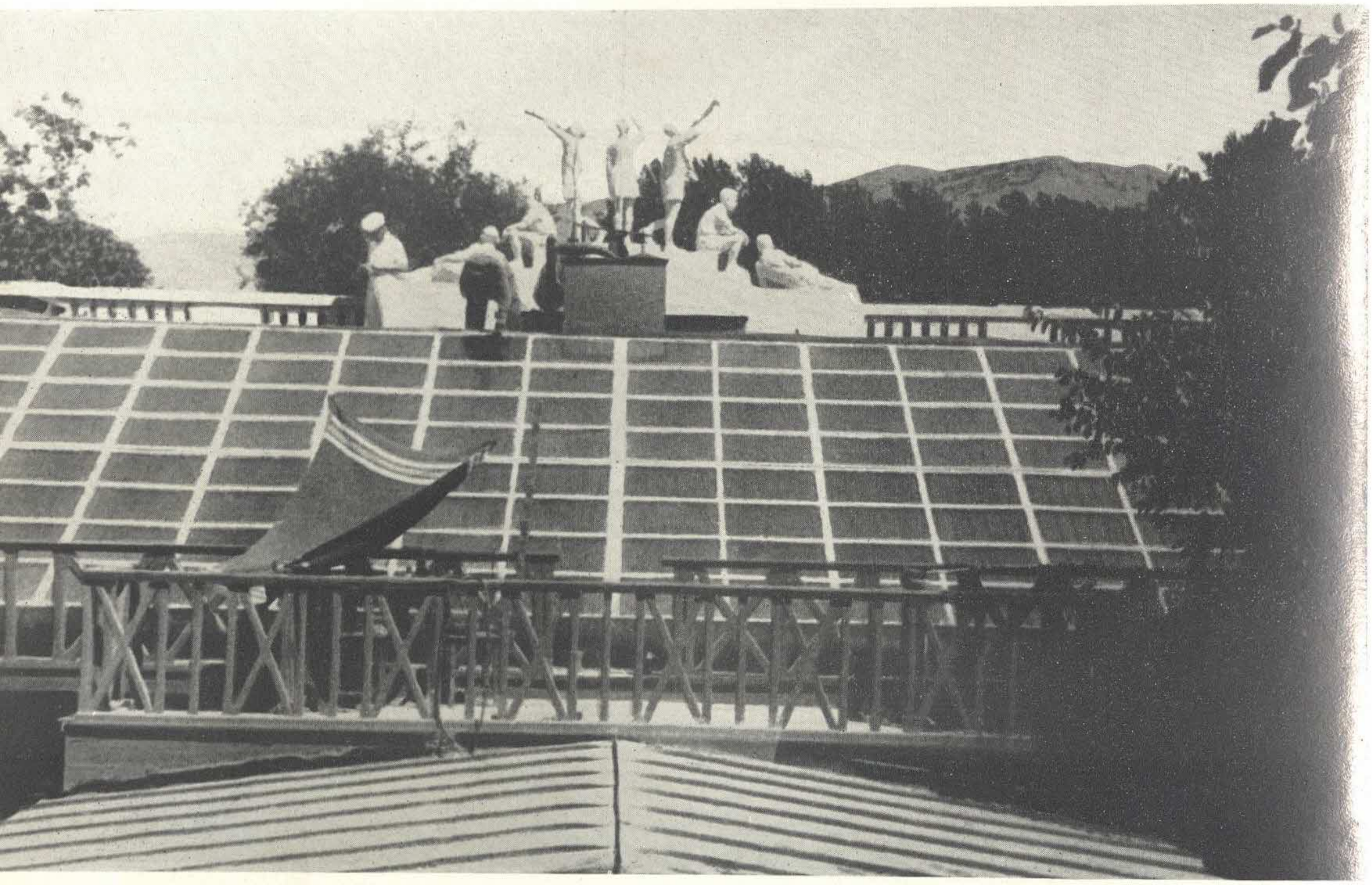
III*d*

A solar water heater with a 12 m.^{2} parabolic cylinder mirror. Capacity: 400 litres a day.

Chauffe-eau solaire muni d'un miroir cylindro-parabolique de 12 m^2. Débit : 400 litres par jour.

Calentador de agua, que funciona a base de la energia solar, dotado de un espejo cilindro-parabólico. Capacidad: 400 litros diarios.

(Cf. p. 155.)

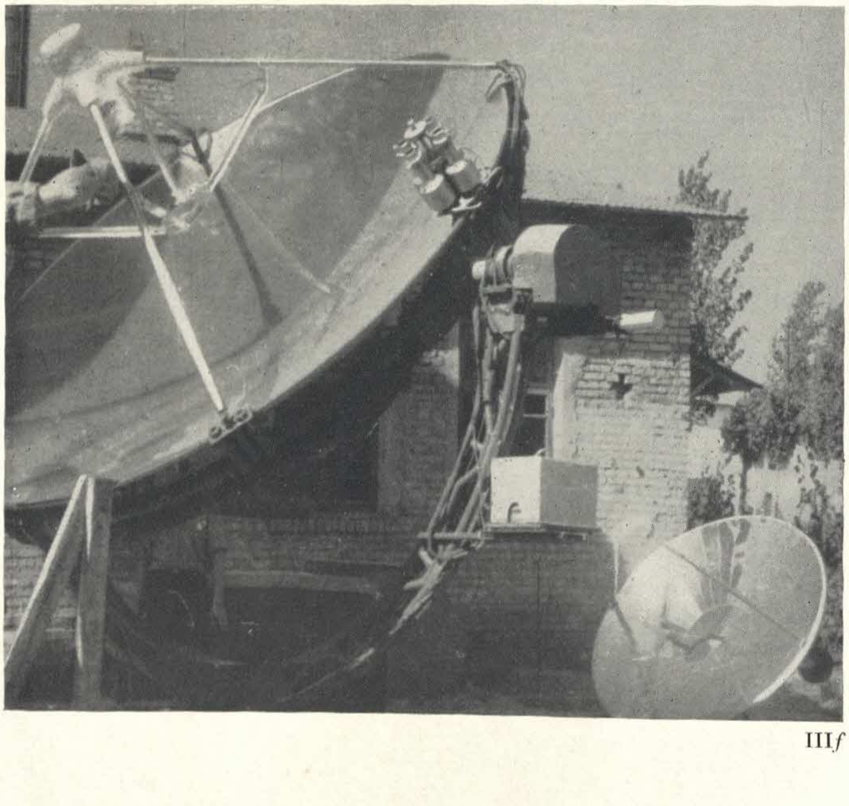


The solar water heater.

Le chauffe-eau solaire.

Calentador solar de agua.

(Cf. p. 156.)



Installation for obtaining high temperatures. It has a silvered glass mirror 2 metres in diameter.

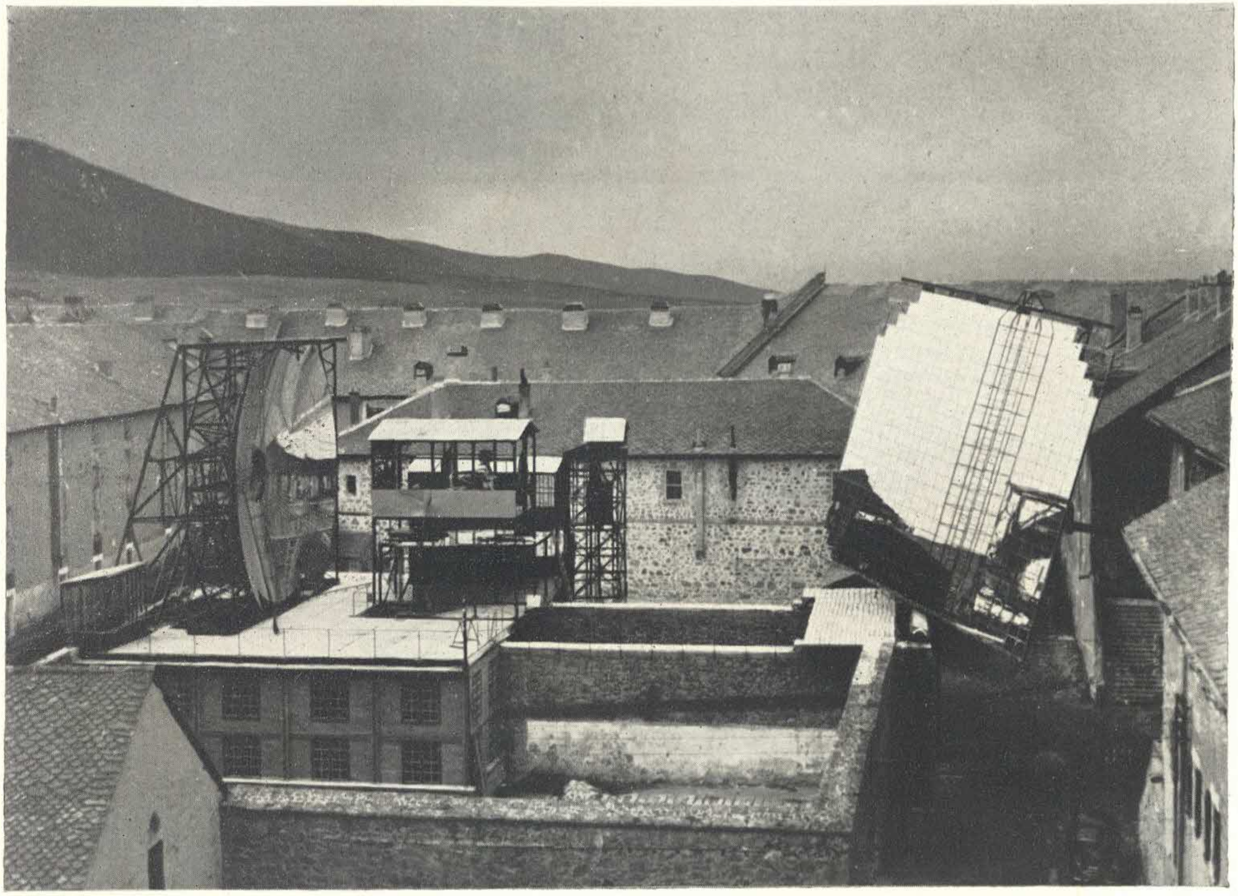
Installation permettant d'obtenir des températures élevées. Elle est équipée d'un miroir argenté de 2 m de diamètre.

Instalación para obtener altas temperaturas. Tiene un espejo azogado de 2 m de diámetro.

(Cf. p. 156.)

III*f*

IV*a*

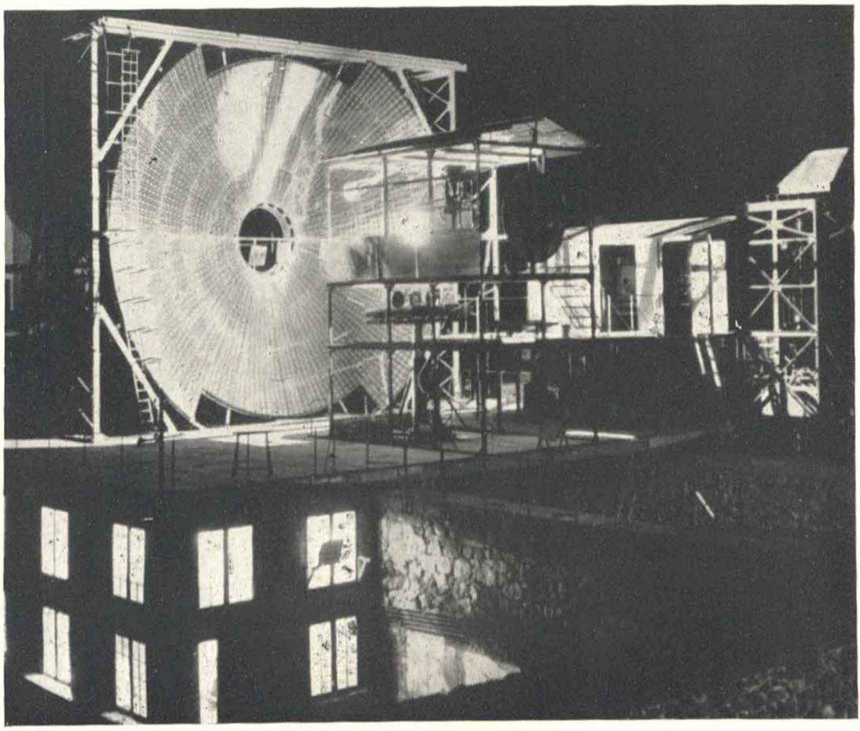


Bird's-eye view of the Mont-Louis installation.

Vue d'ensemble de la grande installation de Mont-Louis.

Vista de conjunto de la gran instalación de Mont-Louis.

(Cf. p. 162.)



The big parabolic mirror at Mont-Louis (night setting).

Vue du grand miroir parabolique de Mont-Louis (réglage de nuit).

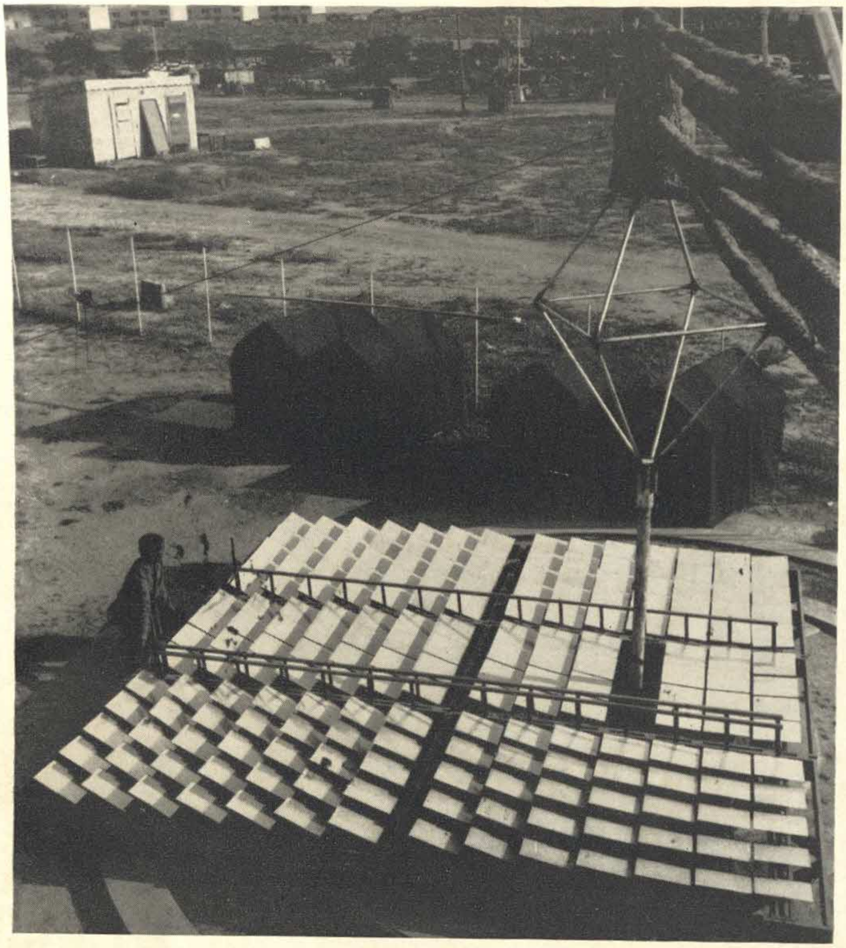
Vista del gran espejo parabólico de Mont-Louis (regulación nocturna).

(Cf. p. 167.)

Photos/Fotos : Laboratoire d'énergie solaire de Mont-Louis.

IV*b*

V*a*

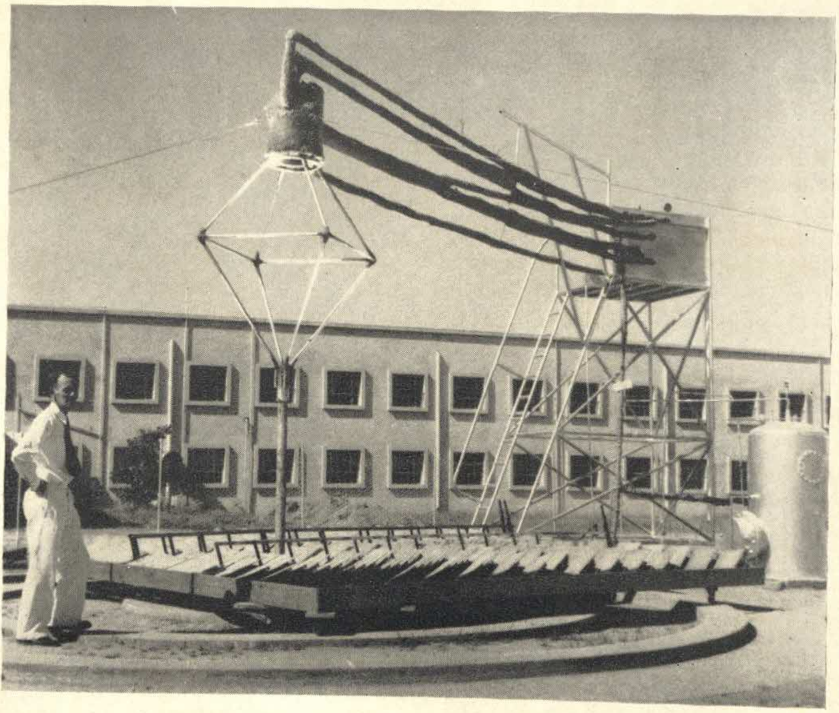


View of semi-articulated concentrator.

Vue de l'installation semi-articulée.

Vista de un concentrador semiarticulado.

(Cf. p. 212.)



Experimental semi-articulated concentrator erected at the National Physical Laboratory during 1954.

L'installation expérimentale semi-articulée réalisée en 1954 au Laboratoire national de Physique.

Concentrador semiarticulado instalado en el Laboratorio Nacional de Física, en 1954.

(Cf. p. 212.)

Photos/Fotos : Mehta, New Delhi

V*b*

Europe the corresponding valleys have mostly fertile arable soil and are often densely populated, and for these reasons it will not pay to use them as water reservoirs. Hence the hydraulic power stations of southern Europe are often prevented from utilizing hydraulic power to the same extent as is done in Scandinavia. In spite of these facts, hydraulic power works are still being built and enlarged in southern Europe. From this it would appear that the kwh. price, is after all, not the only decisive factor. The necessity of securing a supply of power also weighs heavily, apart from the fact that such power works are often established for the purpose of alleviating unemployment—a factor which may also be taken into account in connexion with construction of wind power plants.

The durability or life of a wind power plant, also, is decisive when it comes to judging it as a profitable proposition.

Experience shows that it is possible to construct durable wind power plants if they are suitably built.

A windmill at the Holboek motor works, Denmark, has been running since 1921, without requiring repairs or replacements. The frame has not even been painted since it was erected. All parts of the mill are made from standard section iron and steel, except the shutters of the mill sails, which are wooden slats. It has not been necessary to replace these, either. When constructing wind motors, wherever two iron plates are bolted together so that air and water have totally or partly free access to the contacting surfaces, pronounced corrosion and rusting will appear. This will not happen if such surfaces are coated with red lead before being bolted together and later on carefully painted so that air and water cannot penetrate.

If wind power plants are constructed of iron, steel, aluminium and cement a considerably longer life may be expected than is the case with parts of machinery, such as boilers, steam turbines, internal combustion motors, which are exposed to high temperatures.

LES AÉROMOTEURS

par

J. JUUL

RÉSUMÉ

L'auteur fait d'abord un bref historique de l'évolution de l'équipement énergétique de l'agriculture danoise depuis soixante-dix ou quatre-vingts ans environ. Au début du siècle, quelque trente mille éoliennes alimentaient des exploitations agricoles en courant électrique. Les importants travaux de La Cour sur l'utilisation des éoliennes comme génératrices d'énergie électrique ont accéléré l'électrification des exploitations rurales danoises, mais la concurrence des grandes centrales équipées de turbines à charbon et à mazout, capables d'alimenter toute une région, a réduit le nombre des aéromoteurs à un chiffre insignifiant. Il est néanmoins évident qu'un vaste réseau de distribution comme celui du Danemark peut être alimenté par de multiples petites stations telles que les éoliennes et les essais en ce sens ont été activement menés. Dans une région aride et semi-aride, il serait possible de mettre à profit l'expérience acquise au Danemark pour dresser les plans d'un réseau de distribution alimenté par un grand nombre d'éoliennes.

L'auteur rend compte ensuite des recherches faites au Danemark, principalement sous sa direction, sur l'utilisation de l'énergie éolienne pour l'alimentation d'un réseau de distribution existant en courant alternatif triphasé.

Trois types d'anémomètres ont été employés pour mesurer l'énergie du vent, mais la majeure partie des données provient de petits anémomètres électriques (fig. 1*c*). L'auteur énumère ensuite, et commente, les différents facteurs qui interviennent dans le choix des sites d'observation.

L'importance de la forme des pales du rotor est évidente ; des recherches faites en soufflerie au Danemark ont montré que le profil représenté sur la figure 1 donne le meilleur rendement. Il est également apparu que les dispositifs montés sur les pales — notamment les volets de freinage — ne doivent jamais s'éloigner du profil idéal, sauf au moment du freinage ; à la vitesse périphérique optimale, une hélice à trois ou quatre pales n'a plus sur une hélice à deux pales l'avantage qu'elle avait à plus basse vitesse.

L'auteur décrit ensuite la construction de l'éolienne

expérimentale de Vester Egesborg. La rupture initiale des pales par fatigue du métal a été évitée grâce à des renforts qui permettent aux pales de résister à la pression du vent et à l'action de la gravité. L'appareil ainsi perfectionné fonctionne depuis avril 1951 sans interruption, sauf arrêts pour entretien. Une deuxième éolienne expérimentale — cette fois par reconversion d'une machine plus ancienne — a été installée en 1951, en tenant compte des résultats obtenus à Vester Egesborg.

Le rendement des éoliennes expérimentales est mesuré au moyen de wattmètres enregistreurs et de wattmètres de précision à lecture directe et la quantité d'énergie produite, en kWh, avec des compteurs électriques ordinaires ; on détermine aussi la consommation des génératrices en K sin h. La figure 5 indique le rendement de ces éoliennes et la figure 6 leurs caractéristiques ; cette dernière fait ressortir la nécessité d'adapter chaque éolienne au régime local des vents. Le tableau de la page 70 donne les quantités annuelles d'énergie produite par ces installations.

La construction d'une éolienne exige une connaissance approfondie des contraintes auxquelles ses différents éléments seront soumis. La figure 7 montre schématiquement l'action du vent sur une pale. L'éolienne de Vester Egesborg était conçue de façon à pouvoir mesurer la pression axiale. Les conclusions qui ressortent de la figure 8 ne s'appliquent naturellement qu'à une hélice à deux pales. Pour parer aux phénomènes de résonance, il faut éviter que la fréquence du pylône coïncide avec celle de la pression axiale. Les pylônes qui offrent au vent une surface pleine engendrent des oscillations et peuvent également provoquer des variations momentanées de l'intensité et de la direction de la poussée du vent sur les pales, d'où des phénomènes de fatigue. Les pylônes en treillis parent à ces inconvénients. Les pales en bois sont faciles à modeler mais ont tendance à gauchir ; les pales modernes sont donc en acier avec renforts.

L'auteur a calculé le prix de revient de deux modèles de génératrices éoliennes : le premier, à un seul rotor, n'est que la reconversion d'un vieux moulin à vent hollandais, tandis que le second est un modèle nouveau à double rotor capable d'utiliser les vents plus rapides qui soufflent à une plus grande hauteur. Le prix de revient du kW installé s'établit à 140 dollars des États-Unis pour le premier modèle, et à 112 pour le second.

Pour conclure, l'auteur étudie l'aspect économique des génératrices éoliennes futures. En Scandinavie, les coûts de construction d'une centrale éolienne et d'une centrale hydraulique sont à peu près équivalents, alors qu'en Europe méridionale, le prix du terrain consacré aux barrages étant beaucoup plus élevé, la construction d'usines hydro-électriques revient bien plus cher. La durée d'utilisation est également un facteur important. L'expérience montre que les éoliennes peuvent rester longtemps en service, puisque celle des usines de moteurs Holboek, au Danemark, fonctionne sans interruption depuis 1921 sans avoir jamais eu besoin de réparations.

AEROMOTORES

por

J. Juul

RESUMEN

El autor esboza la historia del suministro de energía eléctrica para la agricultura danesa durante los pasados setenta u ochenta años. Para suministrar energía a las granjas, a principios de siglo había unos 30.000 molinos de viento. El importante trabajo de La Cour sobre el empleo de los molinos de viento para producir electricidad apresuró la electrificación de las granjas danesas, pero la competencia de los grandes grupos generadores (que funcionan a base de carbón y aceites pesados) capaces de suministrar energía a zonas enteras redujo considerablemente la importancia de los aeromotores. No obstante, es indudable que una extensa red eléctrica, como la que actualmente posee Dinamarca, puede ser alimentada por muchas pequeñas fuentes de energía, como son los aeromotores, habiéndose realizado en ese país trabajos experimentales importantes en tal sentido. En una zona árida o semiárida sería posible utilizar la experiencia adquirida en Dinamarca para organizar una red de suministro eléctrico que obtuviera su energía de un gran número de aeromotores.

A continuación, se describen las investigaciones efectuadas en Dinamarca, principalmente bajo la dirección del autor de esta comunicación, sobre el empleo

de la energía para alimentar de corriente alterna trifásica una red ya existente.

Para medir la energía eólica se han usado tres tipos de anemómetros, aunque la mayoría de los datos se obtuvieron con pequeños anemómetros eléctricos (fig. 1*c*). Se enumeran y comentan los factores que deben tenerse en cuenta en la selección de los puestos de observación.

La importancia del diseño de las palas del rotor es evidente, y las investigaciones realizadas en Dinamarca en un túnel aerodinámico han demostrado que la forma más eficaz es la que muestra la figura 1. También se demostró que cualesquiera dispositivos, como un freno aerodinámico o un plano decelerador, montado en la pala, no deberían apartarse mucho del perfil ideal, excepto durante el frenado. Cuando la velocidad periférica de las palas es óptima, una hélice de 3 o 4 palas no presenta la ventaja sobre una de 2 palas que posee a velocidades menores.

Se describe la construcción de un aeromotor experimental en Vester Egesborg. Al principio, se tropezó con algunas dificultades por la ruptura de las palas debida a la fatiga, las cuales fueron superadas instalando refuerzos para resistir la presión del viento y la acción de la gravedad. El molino funciona sin interrupción desde el mes de abril de 1951, aparte de los períodos en que es objeto de inspección. En 1951 se instaló otro aeromotor experimental —en este caso se trabata de la reconversión de un antiguo molino—, basándose en la experiencia obtenida Vester Egesborg.

Para determinar la eficacia de los aeromotores experimentales se utilizan vatímetros registradores y vatímetros de precisión de lectura directa. Para medir la energía en kilovatios se utilizan contadores ordinarios midiéndose también el consumo de los generadores en K sen. h. La figura 5 muestra el rendimiento de los aeromotores y la figura 6 sus características. De ésta se deduce que conviene ajustar cada aeromotor a la velocidad del viento reinante en la localidad. En la tabla de la página 70 puede verse la cantidad anual de energía producida por los aeromotores.

Al construir un aeromotor es necesario poseer un conocimiento completo de las tensiones a que se hallan expuestas sus diversas partes. El efecto del viento en una pala se muestra diagramáticamente en la figura 12. El aeromotor de Vester Egesborg se construyó de manera que pudiera medirse la presión axial. Los resultados obtenidos aparecen en la figura 8, que es sólo aplicable a una hélice de 2 palas. Es necesario evitar que la frecuencia de la torre coincida con la de la presión axial, para que no se produzcan resonancias. Las torres que ofrecen al viento una superficie no interrumpida producen oscilaciones y pueden causar también alteraciones momentáneas de la fuerza y dirección de la presión del viento sobre las palas, dando origen a fenómenos de fatiga. La construcción en forma de enrejado evita esos inconvenientes. La madera, aunque es fácil de trabajar para dar a las palas la forma deseada, está sujeta a deformaciones, por lo que las palas modernas son de acero con refuerzos.

El autor ha calculado el costo de construcción de dos tipos de generadores eólicos: el primero, del tipo de rotor único, es una adaptación de los antiguos molinos de viento neerlandeses; el segundo es un nuevo tipo de rotor capaz de utilizar la más elevada energía eólica que existe a mayor altura. El costo de instalación por kw se eleva a 140 dólares para el primer modelo y a 112 para el segundo.

Por último se examina el rendimiento económico de los futuros generadores eólicos. Por lo que al costo de construcción se refiere, los generadores eólicos o hidráulicos exigen un presupuesto casi idéntico en Escandinavia, mientras que en Europa Meridional, donde el valor de los terrenos para construir embalses es mucho más elevado, la construcción de centrales hidroeléctricas es considerablemente más cara. La duración de las instalaciones constituye también un factor importante, y los experimentos efectuados con un aeromotor en la fábrica de Motores Holboek de Dinamarca demuestran que pueden tener muy larga vida, ya que ese aparato viene funcionando ininterrumpidamente desde 1921 sin haber sufrido ninguna avería.

DISCUSSION

Mr. Golding. I am delighted to have the opportunity of congratulating Mr. Juul on his paper and, in case members of the symposium do not already know what he has done in Denmark, I would like to say how much we, who are working on the same lines, appreciate his pioneer work in the designing, building, and operation of wind-driven machines. Denmark is the only country in the world in which wind power investigations have proceeded almost continuously since 1890 when Professor La Cour started his work at the Danish State Windmill Research Station at Askov. Mr. Juul who, I believe, was one of La Cour's pupils, is indeed a worthy successor to his teacher. His 45 kw. machine which has been running satisfactorily for some two years, feeding its output into the electricity network, represents an important advance in the direction of economic wind power utilization and we have heard with great interest of the 200 kw. machine which Mr. Juul now has under construction. I am sure we all hope that its operation will prove as successful as that of the earlier machine. It would be interesting to hear from Mr. Juul whether he considers his estimate of 1,000 Danish crowns per kw. is a reasonably firm cost for his 200 kw. machine and also whether he thinks that this size is the largest which can safely be built following the fixed pitch design of blades which he is now using.

PLANNING AND BALANCING OF ENERGY OF SMALL-OUTPUT WIND POWER PLANT

by

U. Hütter

SELECTION OF THE SPECIFIC OUTPUT

Comparison of a map of central Europe marking the location of all old windmills [1][1] with a map of the same area showing the statistically determined lines of equal specific density of wind energy [2, 14], clearly indicates that, during the past centuries, the utilization of wind energy was profitable only if the mean annual wind velocity was higher than 3.5-4 m./sec., and the specific density of the gross raw energy E was higher than 500 kwh./m.² per year.

Gross raw energy is understood to mean that amount of energy which an ideal wind power plant would be able to produce, that is, one not affected by any losses caused by twist, friction, conversion, transmission, or adaptation, and utilizing every wind intensity per square metre of propeller-swept area.

$$E_0 = \frac{8760 \times 0.5962}{102} \times \frac{\gamma}{2g} \int_{t=0}^{t=1} V_{ot}^3 \, dt$$

(8,760 hours/year; 102 mkg./kw.; 0.5962 = $C_{1\ ideal}$; γ = air density; g = acceleration due to gravity; V_{ot} = wind velocity.)

In actual practice only much lower values can be expected, not only because of the numerous kinds of losses occurring in transforming the wind power into energy for everyday use [9, 10], but also because the power offered by the wind can be utilized only to the extent determined by the power capacity of the machine itself.

A comparison of the cost of construction of machines having the same propeller diameter but different installed output shows that a design for too small as well as for too large a possible output will be uneconomical. With reference to the energy obtainable, under otherwise identical conditions, a minimum in expense and thus a maximum in profit may be obtained with a plant the size of which depends upon the wind conditions at the place of installation [11].

Fig. 1 shows the quotient of the cost of manufacture of a wind electric plant and of the sum of the yield in kwh. over a period of 10 years of operation for a plant installed in a valley with low wind and one in a windswept mountain area of central Europe.

The rather flat minimum of the rentability factor as defined in Fig. 1 and the desire to obtain a considerable power output in spite of relatively low density of wind energy may be a temptation to build for maximum inherent power capacity. But it must be remembered that owing to the increasing irregularity of the available energy the worth of the raw energy decreases as the inherent power capacity of the machine increases.

Although this fact does not become entirely apparent until a comparison is made between the disordered energy summation curves which can be plotted as continuous functions of the time, it can also be basically recognized by the ordered summation curves.

In the power producing industry the period of use

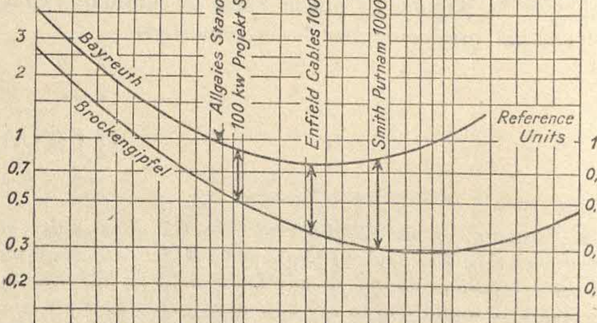


Fig. 1. The relative factor of economy: building costs per yield in kilowatt-hours of low wind valley region of central Germany and high wind mountain area of northern Germany.

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[1] The figures in brackets refer to the bibliography on page 88.

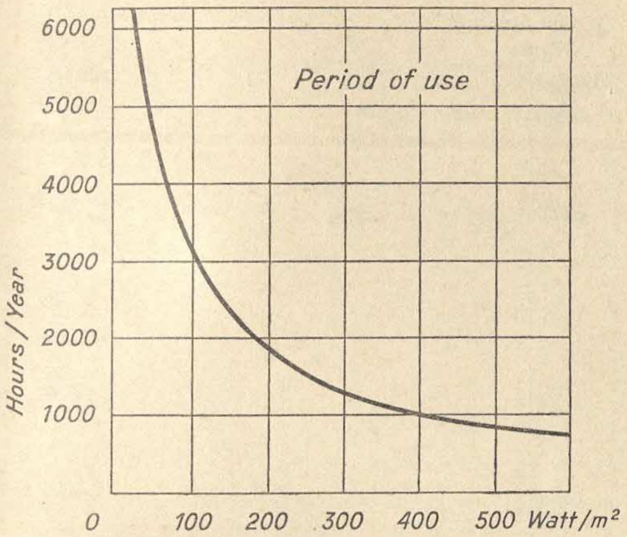

Fig. 2. Service life of a wind power plant in accordance with specific installation.

of a machine is normally taken as a measure of uniformity. Given the same distribution of wind frequency the possible period of use of the wind power plant decreases as its inherent power capacity increases (Fig. 2).

Moreover the length of time increases during which there is no power output at all, since in the larger machines the absolute losses under partial load conditions consume the total energy input.

The fundamental similarity of wind frequency lines permits the generally valid approximate representation of the available energy per unit of propeller-swept area as a function of the average wind velocity and the specific power output (i.e. inherent power capacity per unit area) (Fig. 3).

Since, except under unusually favourable conditions, the mean annual value of the wind velocity of the areas generally to be considered for utilizing wind energy lies between 3 and 6 m./sec. [4, 5, 7, 9, 16, 18, 19, 20], it is hardly worth while with machines intended for use by an individual consumer to make their output larger than 100 watts per m.^{2}, since with increased power capacity the output in kwh. increases at a much smaller rate than the corresponding manufacturing costs.

Naturally, this does not apply to machines designed to feed a certain amount of supplementary energy into an existing public power line and erected at specially selected, windy locations [8]. Also with single consumer plants in very favourable locations such as in tropical coastal areas, on high mountains, or on islands, where the average values of the wind velocity over long periods of time lie between 7 and 10 m./sec., machines may without objection be installed which will produce 200 watts/m.^{2} or more.

In any case the efficiency of a wind power plant is primarily determined by its blade-swept area rather than by the inbuilt power capacity. This power capacity is only of secondary influence on the effective average power output and this latter quantity is the decisive factor in determining the type of plant to be used.

DETERMINATION OF ENERGY SUPPLY

Since the continuous local fluctuation of the velocity of the wind due to turbulence permits a direct supply of raw energy only in those cases in which the time structure of the available power is of no interest, a knowledge of the relation between average velocity and yield in kwh. over a certain period of time is of more practical value than knowledge concerning the connexion between the output and the flow velocity, which can be definitely determined only in a wind tunnel.

A continuous measurement of the wind speed by means of a Robinson's or cup type anemometer permits a reliable determination of the average value over any period of time. Even though the results may not be read at the end of a certain period, this will not affect the utility of a continuous series of measurements. Therefore this type of measurement, which is often preferred to any other, may also be used for testing the suitability of locations intended for the installation of wind power plants, to carry out comparisons in the field, to find the best possible location, as well as to determine the effect of any obstacles, differences in altitude, etc., without requiring any complicated methods for evaluating the results.

For this purpose, a series of very good instruments has already been known for years, most of which, however, have the disadvantage that for reading them

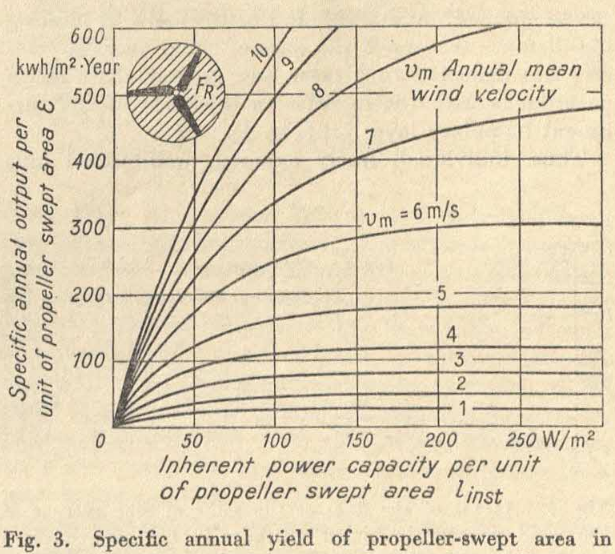

Fig. 3. Specific annual yield of propeller-swept area in accordance with installed output per unit of propeller-swept area, parameter used in annual mean wind velocity.

it is necessary to climb the pole on which they are exposed to the wind. Upon the suggestion of the author, the firm of Lambrecht at Göttingen has now developed a computer, with an indicating panel slanted at 45° towards the ground and provided with large figures which can be read from the ground by means of a pair of field glasses.

The registration of the yield in energy by means of water or electric meters causes no difficulties in measuring. Although the values read at relatively small intervals (one day or less) sometimes deviate considerably, especially if the conditions under which the measurements are carried out differ individually from one another, such deviation will, as the length of the intervals is prolonged, be increasingly compensated so that accurate prognoses of the yield in energy over longer periods of time may be made for a given type of plant, provided average velocity values over long periods of time are available.

With the large mass of meteorological data collected for years in all civilized countries, although only partly evaluated, it is possible at this time to map the supply and utilization of wind energy even of areas which previously have not been individually investigated. Thus, for example, in Germany, a subsequent evaluation of the wind data obtained from the regular climatological measurements carried out as a matter of routine during the last years has offered a valuable insight into the spatial and time structure of the specific supply of energy [2].

Original efforts to draw isovent and isoenergetic maps have been made in a number of countries. These maps show that with similar drives (horizontal pressure decrease), the increase in wind speed as a function of height above ground depends on the roughness of the ground, and where marked differences of ground contours prevail, e.g. as in the transition from open sea to wooded, indulating land or towns, with increasing distance traversed, the lines of equal average velocity are deflected to greater and greater altitudes in accordance with the increase in thickness of the turbulent boundary layer [2] (Fig. 4).

Thus, individual, freely exposed, well-formed hills within a region otherwise offering low ground friction, that is, for example, in coastal regions or in treeless steppes, are specially preferred points for the erection of wind power plants [8].

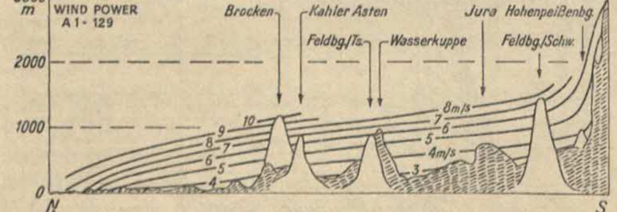

Fig. 4. Ascent of the lines of the same annual average of the wind velocity in higher altitudes in northern-southern direction from the North Sea to the edge of the Alps. (German Meteorological Service).

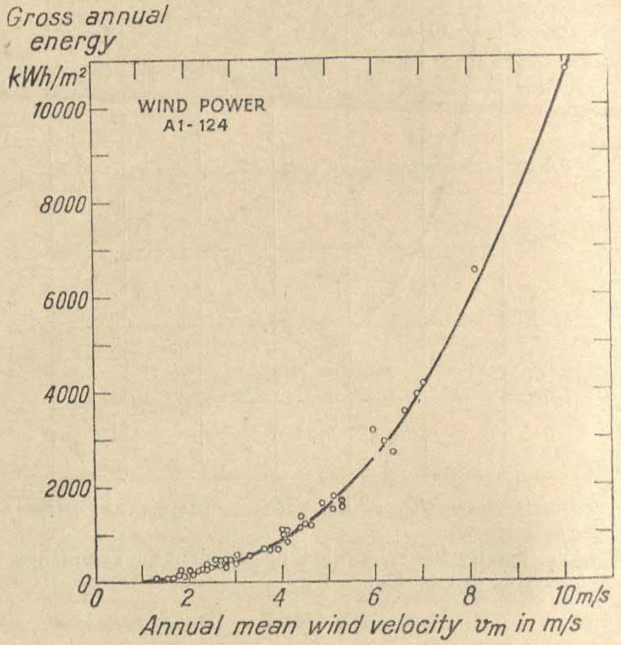

Fig. 5. Annual gross energy of the wind above the annual average of the wind velocity in consideration of all wind intensities. Evaluation from 48 long-term recordings. (German Meteorological Service.)

Even though no results of velocity-performance statistics of wind power plants of suitable size may as yet be on hand, quite accurate data may be obtained for planning new projects by evaluating series of anemograms, since the amounts of gross energy calculated from given wind frequency curves plotted over the mean value of the wind velocity for various locations have the same small range scattering as the data of the effective values obtained in actual practice from measurements carried out on operating machines [2] (Figs. 5 and 6).

ENERGY REQUIREMENTS AND SIZE OF PLANT

If the time structure and amount of the required energy are known, reliable data may thus be given concerning the appropriate size and proper distribution of the necessary wind power plants.

Certain data may be obtained from the investigations carried out in areas in which power is amply supplied and utilized, insofar as the absolute need and the relation between the product of the connected load (L_a) with the selected interval factor (Δt) and the

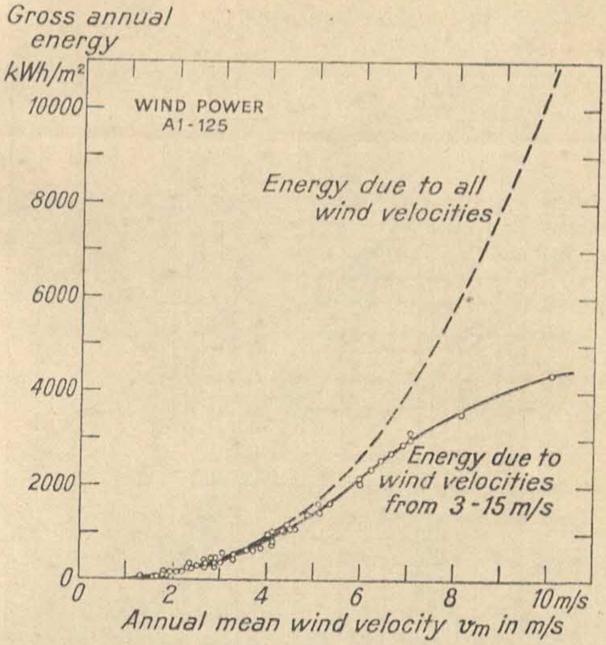

Fig. 6. Annual gross energy of the wind above the annual average of the wind velocity. This evaluation only considers the wind velocities between 3 to 15 m./sec. (German Meteorological Service.)

actual consumption (Σ kwh. effect.) is concerned. This relation, i.e. the ratio

$$e = 100 \frac{\Sigma \text{ kwh.} \times \text{effect.}}{L_a (\text{kw.}) \times \Delta t\,(\text{hours})} \qquad \text{(per cent)}$$

amounts in central Europe in rural households to 2-4 per cent, in city households to 4-6 per cent and in hotels and small industrial enterprises up to 12-16 per cent. With these empirical values the planning of new projects may proceed on the basis of the required load, in which event the energy required for raising water in accordance with the size of the area to be irrigated, the depth of the water-bearing strata, the number of cattle to be supplied, etc., should be calculated separately. Investigation carried out by Zipfel [15] by request of the Energieversorgung Schwaben A.G., and the Western German Curators of Technology for Agriculture [17] shows the annual energy requirements of a fully electrified farm operated by a medium-sized family with a few employees to be about 10 kwh. per day or approximately 3,600 kwh. per year.

If there is only a small stock of cattle and a depth of the water-bearing strata less than 25 m., less than 10 per cent of the above amount will be additionally required to supply the water needs of the household.

The picture changes considerably, however, if in arid or semi-arid regions water has to be raised sufficiently for normal, overhead or sprinkling irrigation of large fields. A supplementary irrigation with about 400 mm. of artificial rain per year by means of low pressure sprinklers and a raising of water from a depth of 20-30 m. amounts to an additional energy requirement of 800-1,200 kwh. per year and per hectare (2,471 acres). This clearly shows that a well-equipped, medium-sized farm in such areas will need at least 6,000-8,000 kwh. per year to satisfy its total energy requirements, i.e. an amount requiring according to Fig. 3 the following minimum values of the propeller-swept area, dependent upon the locally predominant wind conditions:

Annual mean wind velocity in m./sec.	*Required propeller-swept area in m.² for producing 6,000 to 8,000 kwh. per year.*
3	100-160
4	60-80
5	40-60
6	30-40

Of these figures, the order of magnitude rather than the absolute value is interesting because such magnitude presents a new problem in the development of wind power plants, even though for decades a whole series of successful types has been offered on the world market and used by thousands on the thinly populated plains of the earth as follows:

1. Wind driven battery chargers, the marketable sizes of which have the following values:

Propeller diameter	6	8	10	12	14	feet
Propeller-swept area	2.6	4.7	7.3	10.5	14.3	m.²
Voltage	6	12	32	110	110	volts

2. Slow-running wind pumps, operated directly and mechanically, the following sizes of which have been used predominantly:

Propeller diameter	6	8	10	12	14	16	feet
Propeller-swept area	2.6	4.7	7.3	10.5	14.3	18.6	m.²

Both types of machines have proved their usefulness for certain specific purposes. Particularly the wind pump, behind an unimpressive front of an aerodynamic form which seems to require thorough overhauling and appears primitive and out-of-date, hides such perfection and practicability obtained with the simplest possible means that it will surely remain in operation in all parts of the world of low rainfall density for decades to come. Purely as a water pump, its marketable sizes have been properly adapted to the average productiveness of the standard 6 ¼ in. well.

Still, the question remains to be examined whether a central wind power plant may not better be able to solve more universally the supply problems of farms, rural housing developments, postal stations, and smaller and medium-sized workshops which will probably become more and more in need of electric current of standard power supply voltage.

In any case, machines of an entirely new order of magnitude will be required even for the supply of the individual consumer if his needs are to be amply satisfied.

CONTROL FUNCTIONS

In wind power plants the energy forced upon the uncontrolled propeller wheel increases approximately as the third power of the flow velocity, and the axial pressure as the square thereof. Thus, the reliability of its control is the primary problem in obtaining safe operation.

Naturally, with increasing size of the plant, the demands for accuracy and comprehensiveness of control also increase. In addition, with the same general design, the weight of the plant and thus its price increase almost as the cube of the propeller diameter, whereas the propeller-swept area only increases as the square of the diameter. This means that larger plants would be comparatively more expensive than small ones. These considerations entail the necessity of further developing the principal structural features of these plants, aiming at a realization of high rotational velocities.

Most modern wind power plants, which are still, for the most part, in the testing stage, operate with more than 50 m.² of propeller-swept area at maximum tip speed ratio between 6 and 12. The advantages of high tip speed ratio become most apparent if the portion of the propeller surface (*f*) projected on the plane of the swept propeller area (F) is plotted over the planned maximum tip speed ratio[1] of completed plants (Fig. 7).

High rotational velocities and small ratios of propeller surface to total propeller-swept area permit the use of low-cost propellers of large diameter (i.e. of large propeller-swept area).

Because of the high absolute tangential velocities, the effect of squall peaks upon the stresses to which the propeller may be subjected is smaller than with a slow-running machine.

The control operation either by turning the entire propeller blades [9, 13, 15, 16] or parts thereof [6, 12] about their longitudinal axis only requires a relatively small adjusting force and affects the torque as well as the speed of the propeller extremely quickly and effectively (Fig. 8).

If an abrupt squall causes a sudden increase in velocity, the breaking away of the flow on the blade profile causes a considerably slower increase of the tangential force than would be expected from the ratio $L = K.v^3_0$ [12].

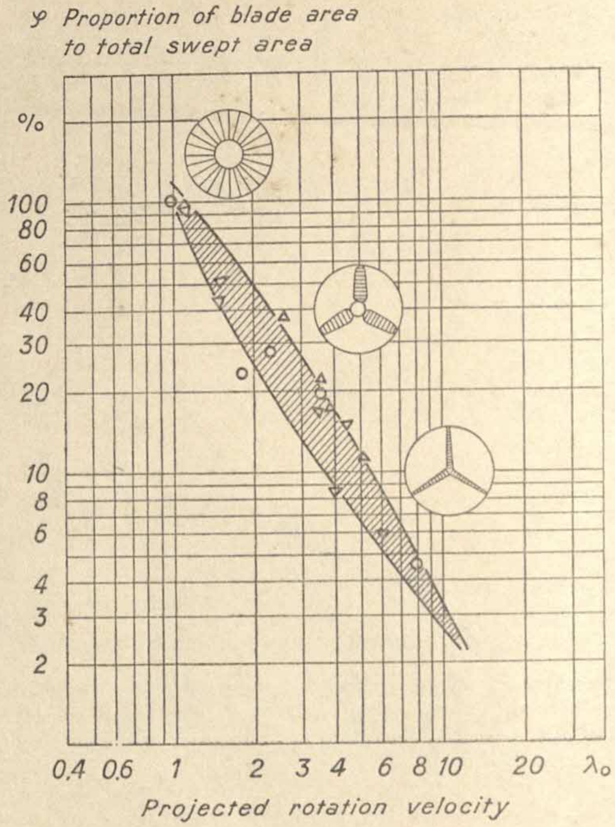

Fig. 7. Relation between the aspect ratio factor and planned high speed of wind wheels and wind with models actually constructed.

When the machine is standing still, the specific resistance (i.e. the resistance coefficient related to the propeller-swept area) lies between 0.03 and 0.08 depending upon the maximum speed, even though the blades are left in the operative position.

These great advantages of a high-speed machine are, however, opposed by the disadvantage of its unfavourable starting action. Such a machine must either be started entirely without load, that is, without being required to overcome any appreciable frictional resistance, or, when passing below a certain speed, its blades must be adjusted to such an extent that the stream will not slide off but continue to act considerably upon the blades.

The accurate shaping of the propeller blades up to their root in accordance with the best possible angular and depth ratio as theoretically prescribed has a considerable influence upon the starting action, as a comparison of the starting torques of well shaped and poorly shaped propellers (Fig. 9) will clearly show.

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[1] Tip speed ratio $\lambda = \frac{r\omega}{v_0}$

r = radius of wing tip
ω = angular velocity = $d\phi/dt$
v_0 = wind (speed) velocity

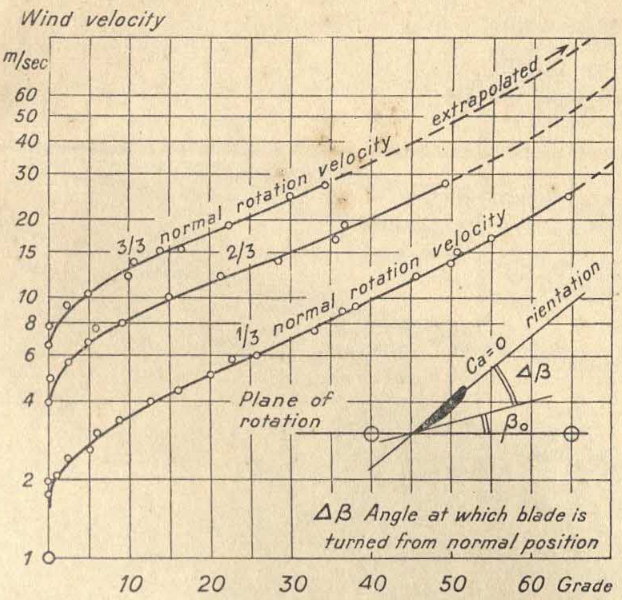


Fig. 8. Relation between angle of blade adjustment and wind velocity with constant wind wheel speeds measured on an Allgaier WE 10 plant, planned maximum speed = 8.

The production of propellers which are carefully and accurately shaped to have the best aerodynamic features causes considerable difficulties. The Allgaier Company composes them of eight steel plate shells which are moulded in large-sized tools in relation to each other and assembled by spot and seam welding in water-cooled welding apparatus (see plate IIa).

For steering the propellers into the wind, the side wheel successfully used for the past 200 years is still being applied, but now is provided with a large self-locking reduction gear between the shaft of the side wheel and the vertical tower axis.

A side-wheel control is to be preferred under all circumstances over any other type since it has happened that in high-speed machines controlled by tail vanes, the propellers were broken by gyratory forces when they were running at a high speed and their direction was suddenly changed.

Apart from certain refinements of the control operation which result in certain small advantages only when the machine is used at a constant speed to supply a public power line, the control mechanism of a wind power plant has merely to provide an accurate limitation of (a) the wind pressure; (b) the speed of rotation; (c) the load; and (d) the voltage. Thus, such control is designed primarily for regulating the losses. However, since the features mentioned are partly functionally related or connected, the blade adjustment may be effected by various types of control devices. For reasons of safety, at least one of these controls should be mechanical and direct, such as is used in the eclipse control of wind pumps.

For the standard plant of 78 m.^{2} of propeller-swept area and power capacity of 6 kw. (110 or 220 volts direct current) or 7.8 kVA. (220/380 volts), 50 cycles, 3-phase current) (see plate IIb) developed by the author at the Allgaier Werke Gm.b.H. at Uhingen, the following control programme has, as a result of thorough investigations and tests, been proved necessary and successful: (a) direction (Fig. 10), mechanical, direct action (side wheel); (b) speed of rotation, centrifugal force, mechanically (direct action), and (c) voltage (output); (d) velocity head, and (e) starting control (indirect action, hydraulically) (Fig. 12).

Since the speed limitation acting directly through a centrifugal governor must have a certain latitude of response because of the unavoidable friction and the stability of the governor, it is desirable that the machine be primarily controlled by hydraulic means for the higher demands upon the regulating accuracy which occur, for example, when using the machine in parallel operation with a public power line.

The hydraulic blade control, and thus the load, the frequency or the voltage may, in turn, be influenced by different control devices through a magnetically operated valve (Fig. 10—TGB7, 02 835).

For battery charging, electro-hydraulic limitation of the voltage has proved to be more successful than any other method. It permits normal, compound shunt-wound generators to be used and permits such accurate limitation of the maximum voltage obtainable that through the charging limitation it will dominate the battery charge so that, for example, when gassing starts, the charge may be gradually reduced to the desired extent.

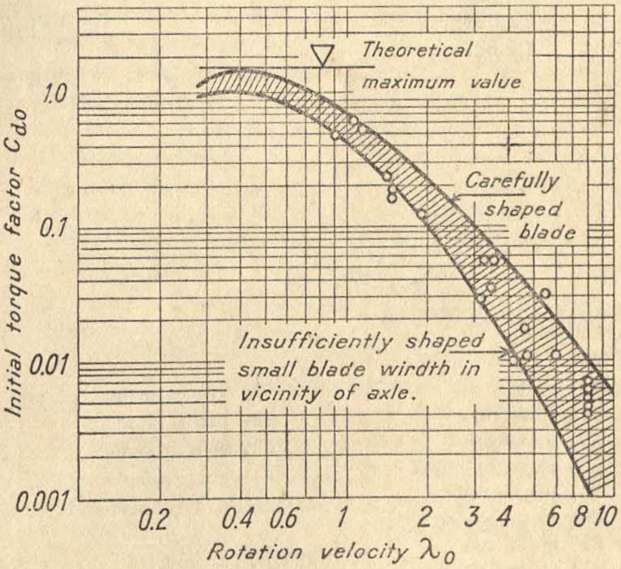
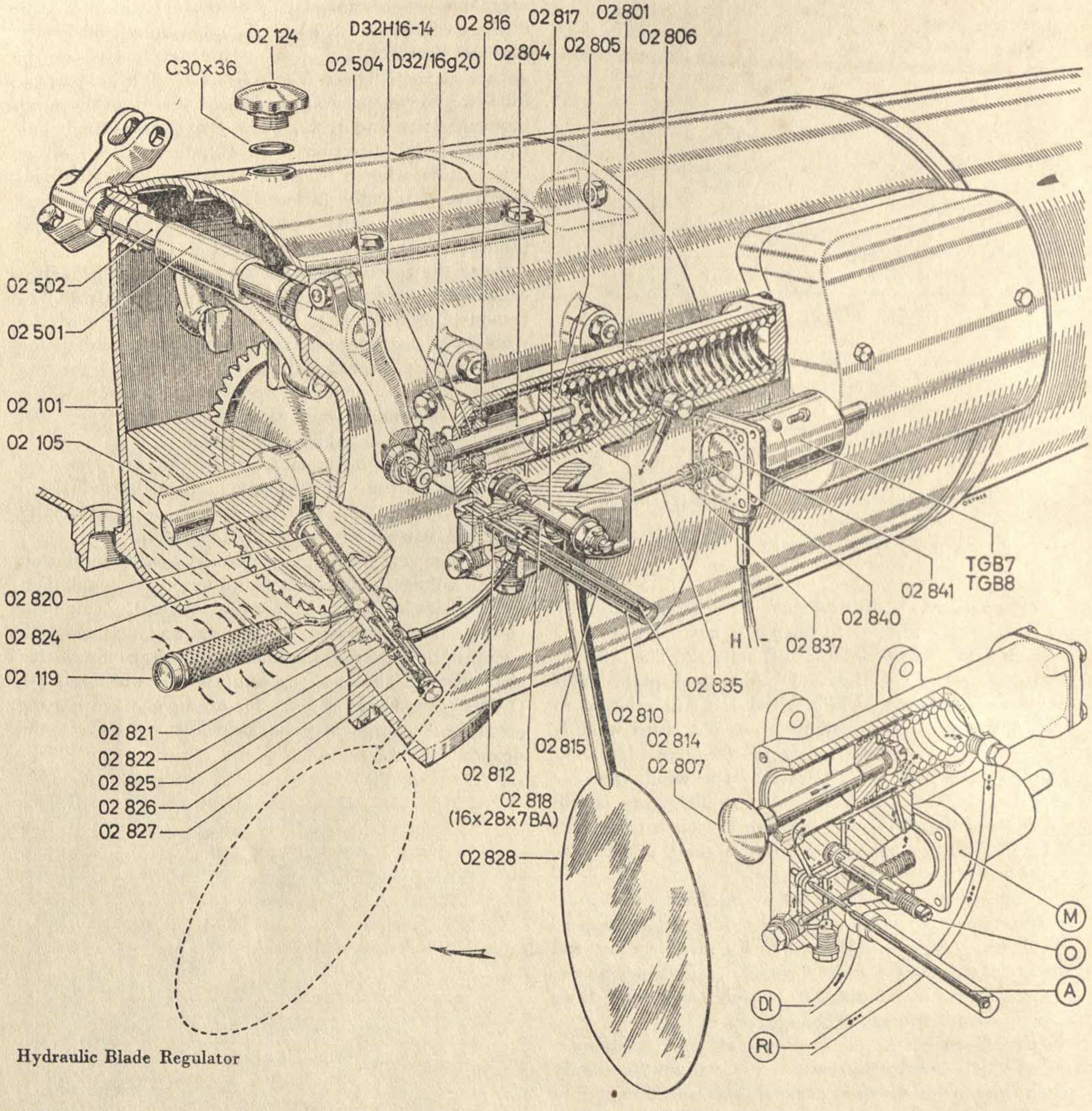


Fig. 9. The zero moment coefficient above the high speed according to 21 wind tunnel measurements on wind wheel models of different design, as mentioned in literature.

Fig. 10. Supplementary hydraulic control of Allgaier Standard Plant WE 10.



02 101	casing
119	filter tube
501	actuator
504	actuator crank
804	piston rod
806	piston spring
810	guide bar
814	control valve
816	cylinder
818	collar
821	pump body
824	pump spring
826	valve spring
828	baffle plate
837	coupling rod
841	guide sheave
D32H16-14	plunger rod sleeve
TGB7	magnet
H	positive lead
D1	pressure pipe
A	starting valve
M	magnetic valve
02 105	Jack (intermediate) shaft
124	air escape valve
502	shift rod
801	hydraulic cylinder
805	piston
807	pressure plate
812	control valve bearing
815	control valve spring
817	rotary slide valve
820	pump piston
822	valve casing
825	valve
827	valve bonnet
835	valve rod
840	magnet spring
C30 × 36	packing ring
D32/16g2,0	plunger rod sleeve
TGB8	magnet
—	negative lead
R1	release pipe

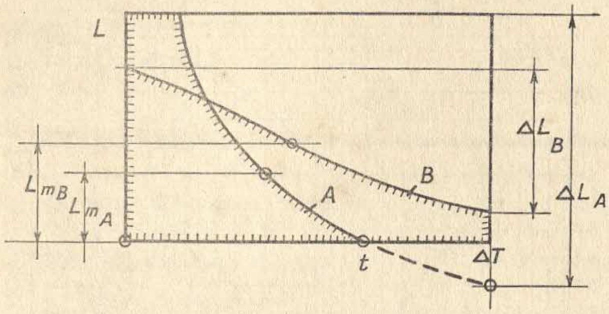


Fig. 11. Definition of the differential output and mean output of two different types of permanent load lines.

Because of the generator characteristics chosen, the wind wheel automatically reduces its speed, so that the plant, when no longer required to supply the full output, will be spared.

When the machine is coupled with a public power line, too early an engagement of a mechanically direct acting speed governor, even when using asynchronous machines, will reduce the output radically, whereas too late an engagement will permit excessive load peaks. Therefore, the electro-hydraulic control also proves successful as a load limitation which may be controlled by a sensitive relay.

This control method has been continuously improved in a series of parallel operation tests which were started in the summer of 1952 on an Allgaier standard plant of 10 m. ∅ at Uhingen [3] and continued since October 1953 at Büsum on the coast of the North Sea by the Western-German Studiengesellschaft Windkraft e.V. (Wind Power Research Society), so that finally under good wind conditions load recordings were obtained which, under a nearly constant load extended over several hours, only showed an average fluctuation of less than ± 8 per cent.

REQUIRED SIZE OF ACCUMULATORS AND *ABLAUFGUTE*[1]

The irregular fluctuation of the wind velocity in the vicinity of the ground is caused by: (a) the turbulence within the ground stratum; (b) the diurnal variations of sun radiation, ground absorption and convection and (c) the overall fluctuation in air pressure and temperature, i.e. the weather. Each of these different influences causes characteristic types of fluctuations.

Especially disturbing are the short-term fluctuations, caused by turbulence with 30 to 100 extremes per hour. On the other hand, these fluctuations are easiest to compensate since the amounts of energy excess and deficiency related to the average yield per hour hardly reach 1 per cent.

The statistical laws of the fluctuations caused by the diurnal variations and changing weather conditions have so far been explored only by general frequency diagrams. Unfortunately, however, immediate conclusions of the process *(Ablauf)* of the lulls to be expected cannot be drawn either from a showing of their relative frequency or from the frequency summation curves.

However, counting the lulls according to their length and an orderly presentation of their frequency permits certain surprising conclusions to be drawn; for example that: (a) in Europe, 80-90 per cent of the lulls last less than 18 hours; (b) the average length of a lull exceeds 6-7 hours only in wind-protected valleys, and (c) the longest lulls, even under very unfavourable, stable, high barometric pressure, hardly ever exceed a period of four days.

However, because of the uncertainty regarding the total process *(Ablauf)*, only indirect conclusions concerning the required balance can be drawn.

The time structure of the energy flow is plainly readable only from the energy summation curves (Fig. 11) which are preferably plotted in oblique coordinates. In order to obtain a measure of the uniformity of these curves, the quality of the process *(Ablauf)* may be defined by the expression:

$$G_A = 1 - \frac{\Delta L}{a\, L_m} \text{ in which } L_m = \frac{1}{\Delta T} \int_0^{\Delta t} Lt \times dt$$

is the medium load in the period of time under consideration and ΔL is the difference between the maximum (L_{max}) and minimum (L_{min}) amount of energy offered. (If Lt is equal to zero already at $t < \Delta t$, the orderly permanent output line must be extrapolated into the negative region in order to obtain L_{min}.) A is an arbitrary factor which may be chosen so that the insufficiently balanced curves will produce $G_A \leqslant 0$. This is true when A equals 3.

Thus, with permanent output curves approximately corresponding to those of river power, G_A will be 0.4 to 0.5. If the balance is so complete, which is by no means required, that the output will remain constant, so that the average output L_m will be equal to the rated output L_N, then G_A will be equal to 1 ($\Delta L = 0$).

An energy accumulator improves the quality of the process *(Ablauf)*. The *Ablauf* curves as balanced by the energy accumulator are obtained by shifting the unbalanced summation curves in the direction of the energy co-ordinate by the distance of the energy accumulator capacity, and by drawing between these two curves a line which no more than touches these curves and ascends as uniformly as possible (Fig. 12). This balancing curve thus empirically obtained may then again be evaluated into an orderly summation curve, a permanent load line, which corresponds to a certain process quality factor G_A.

The process quality factor determined for a given energy summation curve by variation of the assumed

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[1] Process quality.

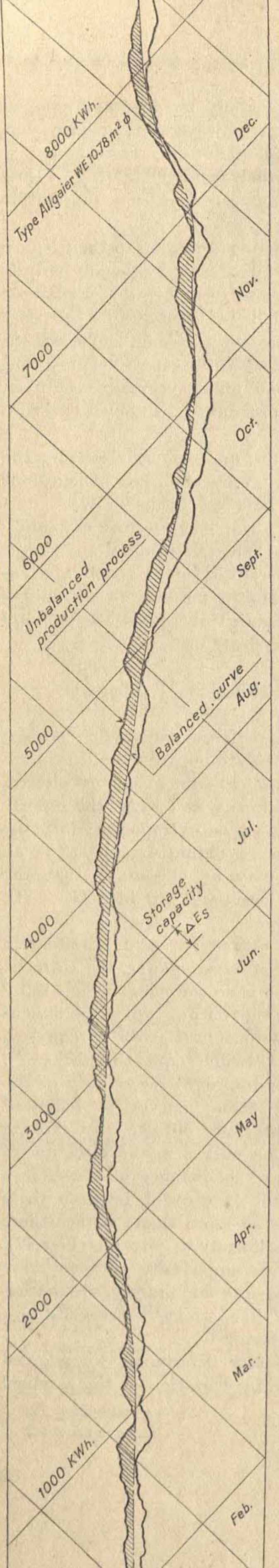

Fig. 12. Energy summation curve, balance curve, and accumulator capacity plotted for a full year. Evaluation of recordings of a station in the vicinity of Augsburg (Bavaria) for a storage capacity of 184 kilowatt-hours at an annual production of 8,420 kwh.

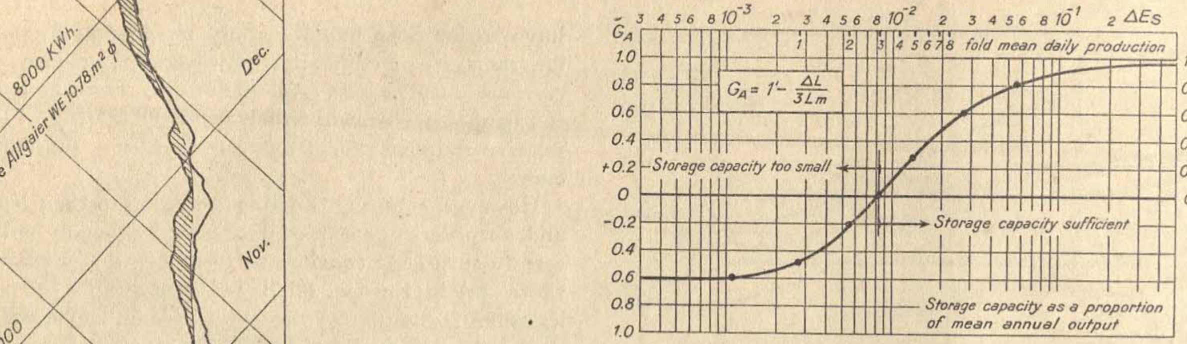

Fig. 13. Example of the course of the *Ablaufgute*—factor for the coefficient $a = 3$ and an energy summation curve according to central German wind conditions.

capacity of the energy accumulator according to the method of evaluation as described is an obvious function of the accumulator capacity (Fig. 13). By means of this function the smallest possible accumulator size may be determined, given the irregularity which may still be regarded as admissible.

However, all known accumulating methods are very expensive and, for example, 1 kwh. stored up by an electro-chemical accumulator (lead or nickel-iron battery), because of the limited life of such units, costs about three times the amount of an energy unit supplied directly.

BALANCE BY ADAPTATION OF CONSUMPTION

Because of the high cost of an energy unit accumulated as electrical energy it is worthwhile to regard the accumulating problem not merely from the generating angle but from the consumer angle as well.

In many cases it is not absolutely necessary to accumulate the required energy in the form of electrical energy. This is true especially for: (a) water raising—storing by dams, in overhead tanks and within the ground; (b) utilization of heat—storing in hot water tanks, accumulating furnaces, or other thermal accumulators; (c) processing of mass products—chopping of straw, conveying of feed, sawing of lumber, rough and fine grinding of grain, producing of chemical products by electrolysis, etc. The expensive electro-chemical storage energy will then be left for the purposes for which it is absolutely required: (d) light, radios, refrigerators and freezers, milking machines and cream separators, washing machines and spinners, sewing machines, vacuum cleaners, immersion heaters, ventilators, etc. For operating small machines such as a drill press, a grinder, a small lathe and hoisting equipment, sufficient current should also be available, supplied by accumulators of suitable size.

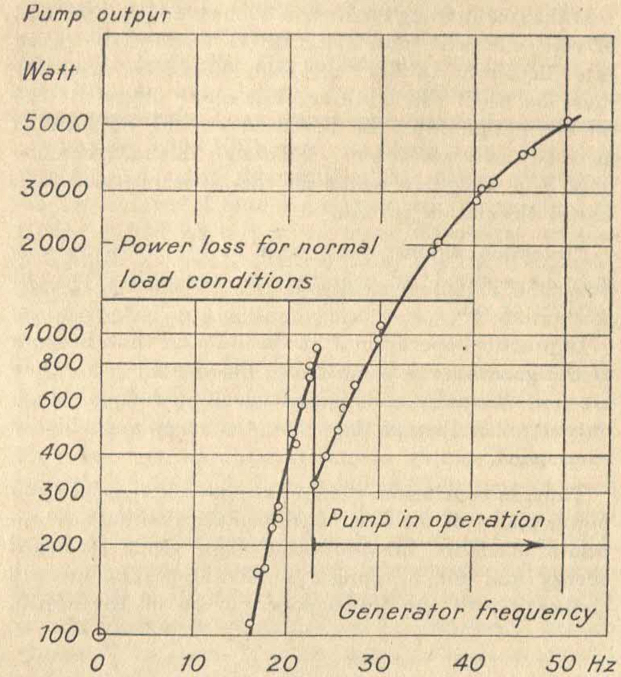

Fig. 14. Power consumption of a 3-phase centrifugal immersion pump in co-operation with a wind power plant Allgaier WE 10/6 kw.

According to the investigations of the EVS previously mentioned [21] as well as those of the Curators of Technology for Agriculture [17], the energy consumption of the above fourth group of consumers is, however, relatively small. Agricultural model developments amply supplied with electrical apparatus and machinery consumed of the total energy consumption: for heating appliances (group b) 70-80 per cent; for driving motors (group c), 12-16 per cent; and for light and small apparatus (group d), 8-14 per cent. These results may, however, not be applicable generally, even though the high amount of heat (although partly necessary for the preparation of human and animal food) required in temperate climate is balanced by the higher energy consumption for cooling and freezing purposes in tropical and sub-tropical climates.

Even cold may be stored. A cold storage plant designed by the Brown, Bovery Company for co-operation particularly with the Allgaier 6 kw. standard wind power plants is capable of storing 44,000 thermal units for long periods of time. For completely freezing the eutectic brine in the cold storage plant approximately 30 kwh. are required. Within 10 days, only 35 per cent of the stored cooling power will be lost to the outside.

Water raising which is not dependent upon any electro-chemical storage of energy evidently plays a more important part in arid than in the temperate zones. Therefore, in these areas a large part of the required energy will be consumed independently of any expensive and sensitive storing methods.

WATER RAISING BY ELECTRIC PUMPS

For water raising, the high-speed machine has also proved successful, if the energy is transmitted from the wind power plant to the pump by electric current. Especially when using centrifugal immersion pumps together with underwater 3-phase current motors significant advantages are obtained: (a) The pump and wind motor do not have to be mounted at the same place. The wind power plant may be erected on a windy hill, while the well with the pump may be dug hundreds of metres away in a low place. (b) One wind power plant may be used to operate several pumps if a single well does not have sufficient water to consume all the energy produced by the plant. (c) Several wind power plants may be used to operate a single large pump station of high efficiency. (The pump station Neundorfer Hammrich of 64 kw. operated by 8 Allgaier wind power plants drains a marsh area at the mouth of the River Ems of 500 ha. (1,235 acres) (Fig. 11). (d) The manufacture of wind power plants may be carried on independently of the manufacture of the pumps. A single type of plant may be used to operate any type of new or already installed pump, and thus any form of pump application may be used (raising of water from deep or low wells, sprinkling, irrigation, drainage, etc.). (e) Energy may also be branched off from the electric current produced by the plant for other purposes which may not be apparent until subsequently.

The direct co-operation of a 3-phase current (synchronous) generator and pump motor without any special intermediate controls causes no difficulties either electrically or otherwise.

The measured relation between the rotary speed of the propeller, that is, the generator frequency, and the power consumption by the pump motor shows that the immersion pump will start even before the power consumed has reached the amount of the nominal load losses (Fig. 14).

SERVICE LIFE OF PLANT IN CONTINUOUS OPERATION

The service life of a machine operating outside not only depends upon the methods of preserving its surfaces but especially upon the particular construction used.

In the manufacture of tractors, models with a sheet metal cover over the engine or only simulating such covering have proved very successful. Thick-walled cast iron engine housings constitute the best and longest lasting protection from corrosion.

The sheet metal construction of the propeller blades rotating at a great tangential speed and necessarily having thin walls because of the weight involved, and the forces acting thereon, may be adequately protected by making it of a light metal and by plating or oxidizing it. Shells made of steel plate must be preserved by dip-varnishing them several times, preferably with baking enamel.

More difficult is the sealing of the movable machine parts against oil losses toward the outside and against blown sand and moisture likely to penetrate into the machine.

The question of sealing the machine against oil losses is one of using proper elastic sealing means, as well as an accurate design and proper fit of the respective parts.

The penetration of moisture may be prevented by appropriate ventilation of the inside of the machine and by providing low settling points for the water of condensation.

If the surrounding territory is such that large amounts of very fine drift sand flying in the air must be taken into account, totally enclosed electrical machines must be used. In addition, fine sieve filters for the oil circulation must be mounted on the outside, so as to be easily accessible. Naturally, this may be done only in a design in which all the oil is included in a forced circulation system.

Protection against very high or low temperatures may be secured by choosing the required type and quality of oil.

In practical operation it has been found that, because of the good outside ventilation, the electric generators are not thermally endangered when producing a high output, even though they may temporarily be highly overloaded.

Thus, in conclusion, it appears that high-speed wind power plants of the size mentioned are the most appropriate machines for producing high grade electrical energy and for bringing the advantages of modern civilization to the undeveloped areas of the world.

L'UTILISATION DE L'ÉNERGIE ÉOLIENNE

par

U. Hütter

RÉSUMÉ

L'auteur étudie d'abord les facteurs qui commandent le choix de la puissance spécifique d'une centrale éolienne. Une partie de l'énergie cinétique théoriquement captée par unité de surface balayée est en effet perdue du fait de la flexion des pales, des frottements, des transmissions et de la transformation d'énergie ; d'autre part, la puissance du vent ne peut être utilisée qu'à concurrence de la puissance nominale de la machine. Il importe donc de déterminer le calibre de l'installation en fonction du régime des vents à l'endroit où elle sera montée. Il serait désavantageux de choisir une puissance nominale trop élevée, car plus le régime des vents est irrégulier et plus le rendement en énergie brute diminue quand on augmente la puissance installée. Les frais d'installation augmentent également plus vite que le débit possible. L'auteur donne quelques indications quantitatives sur la valeur optimale de la puissance par unité de surface balayée. La puissance fournie par une génératrice éolienne est essentiellement fonction de la surface balayée, bien plus que de la puissance installée.

La partie suivante traite de la détermination de l'énergie captée et souligne la nécessité de mesurer le rapport entre la vitesse moyenne du vent et l'énergie produite en kilowatts sur une longue période de temps. L'enregistrement du débit énergétique au moyen de compteurs hydrauliques ou électriques ne présente pas de difficultés, mais les valeurs obtenues peuvent varier considérablement pour une même vitesse moyenne du vent lorsque les lectures sont faites à des intervalles relativement faibles (une journée ou moins); au contraire, à mesure que l'écart entre deux lectures augmente, ces différences tendent à s'annuler. Il conviendrait enfin d'évaluer les données météorologiques disponibles en vue de déterminer les emplacements les plus propices à l'installation de génératrices éoliennes.

L'auteur donne ensuite quelques indications sur le choix du calibre et de la répartition des génératrices éoliennes, une fois connues la distribution dans le temps et l'importance des besoins en énergie. Il fournit des statistiques sur les quantités moyennes d'énergie nécessaires à des exploitations agricoles moyennement

équipées d'Europe centrale. Dans des régions arides ou semi-arides, les choses se présentent bien entendu tout autrement, car l'irrigation crée des besoins supplémentaires qui portent la consommation globale d'une exploitation d'importance moyenne bien équipée à 6.000 ou 8.000 kWh par an. Après avoir dressé un tableau indiquant de combien de mètres carrés de surface balayée il faut disposer en vue de produire de 6.000 à 8.000 kWh par an pour différentes vitesses moyennes du vent, l'auteur cite, à titre d'exemple, divers aéromoteurs pratiquement employés à charger des batteries ou à actionner des pompes à mouvement lent.

Il traite ensuite du calcul des génératrices éoliennes du point de vue de la technique et du coût. La puissance communiquée par le vent à une hélice tournant librement est approximativement proportionnelle au cube de la vitesse de l'air et le couple moteur au carré de cette vitesse. Le poids et le prix des installations croissent presque comme le cube du diamètre de l'hélice alors que la surface balayée n'augmente que comme le carré de ce diamètre. Ces considérations, et diverses autres, incitent à construire des génératrices à grande vitesse de rotation. L'auteur examine leurs avantages et leurs inconvénients et indique sa propre solution du problème du réglage. L'orientation et la vitesse de rotation doivent être commandées par action mécanique directe (l'une par rose des vents, l'autre par force centrifuge), tandis que la tension de sortie, la vitesse et le démarrage sont réglés hydrauliquement au moyen d'une soupape électro-magnétique.

La section suivante porte sur la capacité d'accumulation nécessaire en fonction des variations de la vitesse du vent au voisinage du sol. Pour étudier la distribution dans le temps du flux d'énergie et obtenir une certaine uniformité, l'auteur donne une expression mathématique de ce qu'il appelle le taux de rendement de l'installation, dont les éléments sont la charge moyenne dans la période considérée et l'écart entre les maxima et minima de l'énergie offerte. Ce taux peut être déterminé pour toute courbe globale d'énergie et variera selon la capacité d'accumulation de l'ensemble du circuit de production d'énergie. Pour une courbe donnée, le taux de rendement est donc fonction de la capacité d'accumulation et permet de déterminer la plus basse capacité d'accumulation admissible compte tenu des irrégularités prévisibles de l'énergie éolienne.

Dans bien des cas, l'accumulation n'est pas indispensable, par exemple, pour l'élévation de l'eau, le chauffage ou le traitement de produits par grandes quantités. Elle l'est pour une quatrième catégorie où figurent : éclairage, radio, réfrigération, traite mécanique, etc.

L'élévation de l'eau par pompes électriques convient particulièrement à l'éolienne ; en effet, il est possible d'installer la pompe à quelque distance, d'employer plusieurs génératrices pour alimenter la même pompe ou d'alimenter plusieurs pompes à partir de la même génératrice.

Une installation peut fonctionner en service continu pendant très longtemps même en région désertique, à condition de l'entourer des précautions nécessaires.

La conclusion générale est que pour transformer l'énergie du vent en électricité, la meilleure machine est l'aéromoteur à grande vitesse de rotation.

UTILIZACIÓN DE LA ENERGÍA EÓLICA

por

U. Hütter

RESUMEN

El trabajo comienza con un examen de los factores que determinan la selección de la potencia específica de un grupo generador accionado por la energía eólica. La cantidad de energía eólica teóricamente captada por unidad de área no sólo se halla reducida por pérdidas debidas a la plexión de las palas, la fricción, la transmisión y la transformación de un tipo de energía a otro, ya que la energía proporcionada por el viento sólo puede utilizarse en la medida determinada por la capacidad nominal de la propia máquina. Por consiguiente, es esencial que el tamaño del grupo generador esté determinado en función de las condiciones del viento en el lugar de emplazamiento. Una capacidad nominal demasiado elevada es desventajosa ya que, debido a la irregularidad creciente de la energía disponible, la potencia teóricamente utilizable dis-

minuye en razón del aumento de la capacidad nominal. Los gastos de instalación también aumentan más rápidamente que la potencia utilizable. En el estudio se dan algunas indicaciones cuantitativas en lo que respecta a la producción de energía por unidad del área del círculo barrido por las palas. La potencia de un generador accionado por el viento es esencialmente una función del área del círculo barrido por las palas más bien que de la capacidad nominal.

La sección siguiente trata de la determinación de la energía captada y subraya la necesidad de medir la relación existente entre la velocidad media y el rendimiento en kilovatios durante un largo período de tiempo. El registro del rendimiento de energía con contadores de agua o de electricidad no resulta difícil, pero los valores obtenidos difieren considerablemente para una misma velocidad media del viento si los valores se comprueban a intervalos relativamente cortos (un día o menos) ; pero al aumentar los intervalos esas diferencias quedan cada vez más compensadas. Deberían evaluarse los datos meteorológicos disponibles a fin de determinar los mejores emplazamientos para la instalación de los grupos electrógenos accionados por el viento.

El autor da algunas indicaciones acerca del tamaño apropiado y sobre la distribución adecuada de los aeromotores una vez conocida la cantidad de energía necesaria y las horas en que debe distribuirse. Se poseen datos acerca de las necesidades de energía de granjas bastante bien equipadas en Europa Central. La situación es distinta, desde luego, en las zonas áridas o semiáridas donde las exigencias adicionales del riego elevarán la necesidad de energía de una granja bien equipada de tamaño medio a un total de 6.000/8.000 kWh anuales. En una tabla se relaciona la velocidad media del viento y el área del círculo barrido por las palas en metros cuadrados necesarias para producir de 6.000 a 8.000 kWh anuales; así como ejemplos de aparatos existentes tales como cargadores de baterías accionados por el viento y bombas eólicas de velocidad lenta.

Después se examina el cálculo de los factores técnicos y económicos con referencia a los aeromotores. La potencia impartida a unas palas no reglables aumenta aproximadamente en razón directa al cubo de la velocidad del viento, y la presión axial al cuadrado de la misma. El peso y precio del aeromotor aumenta en razón directa al cubo del diámetro de las palas, mientras que el área del círculo barrido por aquéllas sólo aumenta al cuadrado del diámetro. Esas y otras consideraciones aconsejan la construcción de hélices de elevada velocidad de rotación. Luego el trabajo examina las ventajas y las desventajas de esos molinos y se indican soluciones del problema del reglaje. La orientación y la velocidad de rotación son reguladas por una acción mecánica directa (veleta y fuerza centrígufa respectivamente) mientras que el voltaje de salida, control de velocidad y arranque son regulados hidráulicamente por medio de una válvula magnética.

El autor examina después la capacidad de acumulación en relación con las variaciones de la velocidad del viento a ras del suelo. Para estudiar las características del viento durante las diferentes horas y obtener una medida de uniformidad, el autor da una expresión matemática a lo que él llama "Ablauf" (tasa de rendimiento) en función de la carga media en el período de tiempo que se examina y la diferencia entre la cantidad máxima y mínima de energía disponible. Ese factor puede determinarse para cualquier curva global de energía y variará según la capacidad de acumulación del circuito de producción de energía. Dada una curva determinada, el "Ablauf" es por tanto una función de la capacidad de acumulación. Esa función permite determinar la capacidad mínima de acumulación admisible teniendo en cuenta las irregularidades previsibles de la energía eólica.

En muchos casos no es necesario recurrir a la acumulación por ejemplo, para la elevación del agua, la calefacción o la fabricación de productos en serie. Hay, sin embargo, una cuarta categoría de utilización que requiere corriente eléctrica: alumbrado, radio, refrigeración, máquinas de ordeñar, etc.

La elevación del agua por medio de bombas eléctricas conviene especialmente a los aeromotores, ya que puede instalarse una bomba a cierta distancia del molino, y varios grupos pueden hacer funcionar la misma bomba o varias bombas pueden ser accionadas por el mismo grupo.

Tomando las precauciones adecuadas puede conseguirse una larga vida del aeromotor en funcionamiento ininterrumpido, incluso en regiones desérticas.

Los argumentos expuestos en el trabajo sugieren que los aeromotores a elevada velocidad de rotación son las máquinas más apropiadas para producir electricidad a base de la energía eólica.

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DISCUSSION

Mr. Golding. Dr. Hütter, like Mr. Juul of Denmark, is a designer of wind power plant who has been successful in developing a really effective machine. We have been in touch with his work for some years and are now testing an 8 kw. machine of his design. It is very useful to have a paper on this important question of balancing the load against the random power output of the machine and we have been fortunate in having such a full explanation of the question in this paper. Dr. Hütter's division of energy consumption into 4 groups is particularly useful because it enables one to estimate, with rather more precision, the storage required.

His earlier machines drove an A.C. generator, with an over-sized exciter, which could be used for battery storage, so that essential light loads could be supplied from the battery during calm spells while heavier loads were supplied from the A.C. machine when there was plenty of wind. I believe that more recent machines have been D.C. and, in view of the increased capital and maintenance cost usually associated with D.C. machines, I should like to hear from Dr. Hütter why he has decided to use them rather than the original A.C./D.C. combination

THE ECONOMIC UTILIZATION OF WIND ENERGY IN ARID AREAS

by

E. W. GOLDING

INTRODUCTION

Some 2 per cent of the sun's energy falling on the earth is converted into wind energy and it has been estimated [10][1] that even the small fraction of this total which could conceivably be captured would be equivalent to that produced annually by the burning of some 1,500 million tons of coal. But this capturing has not yet begun on any significant scale. No precise calculation of the present annual energy produced from the wind can be made in the absence of records of the capacities of wind power installations in different parts of the world. A rough—and probably optimistic—estimate would make it less than the equivalent of 500,000 tons of coal per annum. Yet, when the wind blows at 10 m./sec. the power in a column of air 10 m.^{2} in section is 60 kw.

In many areas, even in arid zones, wind speeds of this order of magnitude frequently occur and it is natural to question why, when power is so badly needed for the development of such areas, that from the wind is not more widely used. Clearly there must be good reasons for the neglect of this freely available and inexhaustible source of energy. Probably the most important of these reasons are: (a) insufficient attention has been given, until recently, to the development of machines for practical use on a wide scale; manufacturers have been content to produce very small machines generating electricity for isolated rural premises or somewhat larger, non-electric, machines for water pumping; (b) there has been no general realization of wind power potentialities accompanied by surveys on which estimates of such potentialities could be based; (c) the wind is essentially a source of energy, not of firm power which can be made available on demand. Storage of energy to cater for calm spells has presented a problem. Electrical storage, by batteries, is expensive, while alternative methods of storage, or means of using random energy as and when it occurs, have not been sufficiently studied.

The economic utilization of wind energy, no matter for what part of the world it is being considered, can only come about through three parallel lines of development: (a) the construction of appropriately designed machines at an economic cost; (b) wind surveys to discover the best sites on which to locate these machines, and (c) studies of the means of utilization to ensure, without expensive storage, the full and effective use of all the energy which becomes available.

Briefly, we need good machines, good sites, and full utilization of the energy available.

ECONOMIC OUTLINE

There is much misconception concerning the economy of wind energy. It is frequently thought to be impracticable to use it unless a strong wind blows constantly at the site of the installation. Yet, in fact, a decision on the question can probably be made more easily than for most other methods of power production.

The cost per unit of energy produced by the wind must be considered, not as an absolute value but as a relative one; it must be related to the cost of production by alternative means at the same place.

For the wind, three criteria may be used in determining the energy cost [2, 5]:

1. From wind records taken at the actual site proposed for the wind-driven machine it is possible to estimate with sufficient accuracy the annual specific output (in kwh. per annum/kw.) which could be obtained from a machine with a given operating range of wind speeds (see section on Wind Surveys and the Choice of Sites). The annual average wind speed at a given site is found to vary, from year to year, only between fairly narrow limits—usually within ± 10 per

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[1] The figures in brackets refer to the bibliography on page 101.

cent—so that estimates made from wind records for a year of normal windiness may be relied upon as a good enough indication of the long-term value. Let this specific output be T_s.

2. The capital cost of the machine to be installed is the next important factor. The development of different sizes of wind-driven plant has not yet reached the stage when one can state with precision the cost per kw. for each size, but there are indications—supported by a few actual costs—that these may be of the following order: for capacities under 10 kw.—\$420 to \$560 per kw. (including battery). For capacities from 10 to 100 kw.—\$280 to \$420 per kw. (without battery). For capacities above 100 kw.—\$140 to \$280 per kw. (without battery). Full storage by batteries would not usually be attempted for the larger sizes of machines; only limited storage, to provide essential services such as lighting, during calm spells, would be employed. It is to be understood, of course, that a machine designed for an exceptionally low operating range of wind speeds would be more expensive than one for a higher range. The figures quoted would apply for sites of moderate windiness at which a rated wind speed (i.e. wind speed for full power output) of 40 km./h. would be appropriate. Let the capital cost, in general, be \$C per kw.
3. The annual operating cost for the machine consists, in the main, of interest and depreciation charges to which must be added a maintenance charge of between 1 and 2 per cent of the capital cost. (This allowance for maintenance has been obtained from Danish experience [6] over a long period of years.) With an interest rate of 4½ per cent and depreciation based on a 10 year life for half the cost, and a 20 year life for the other half, the total annual charges would be some 12 per cent of the capital cost. In general, take this to be *p* per cent.

The expression for the cost, in pence, per kwh. of the wind-produced energy, is thus $\frac{pC}{Ts}$ which gives a cost of 1.68 cents per kwh. if $C = \$350$, $p = 12$ per cent and $T_s = 2{,}500$ kwh. p.a./kw.

To judge the economy of wind power under given circumstances the energy cost, so derived, must be compared with the cost of energy from alternative sources, taking into account that the energy from the wind is of random occurrence and must be used as it occurs unless the cost is to be increased by the provision for storage.

It will be shown later that, for a site with a given wind régime, the specific output T_s can be increased by reducing the rated wind speed of the machine to be installed. But this increases the cost per kw., C. It is a design problem to determine, from knowledge of both the wind régime and the influence of the rated wind speed upon construction cost, the best value to choose so that the ratio $\frac{C}{T_s}$ shall be minimum.

To view the matter perspectively, the cost of 1.68 cents per kwh. given, as an example above, is to be compared with at least 3.5 cents per kwh. for the running cost (excluding fixed charges) of energy generated by an oil engine at a site where the price of oil fuel is 9.5 cents per litre. Counterbalancing the higher cost of the energy from an oil engine is the fact that it can be made available at any required time. An oil engine is a source of "firm" power: a wind-driven machine is not. Battery storage to provide (say) one-fifth of the total installed power on demand would increase the energy cost to about double that for random energy only.

WIND SURVEYS AND THE CHOICE OF SITES

The importance of choosing the best possible site on which to install a wind-driven power plant cannot be too strongly emphasized.

The expression for the power P (in kw.) available in the wind is

$$P = 0.0006\ AV^3$$

where A = the swept area in square metres, V = wind speed in metres per second (This becomes $P = 0.000005\ AV^3$ if A is in sq. ft. and V is in m.p.h.).

Since wind speed enters into the expression to the third power (V^3) a considerable increase in the power for a given swept area is brought about by even a small increase in the wind speed.

For small machines the choice of site is usually very limited. If they are driving an electric generator this is a low voltage D.C. machine (because of the need for battery storage) and must be placed near to the premises in order to minimize voltage drop. If the windmill is non-electric, as for water pumping only, it must be installed immediately adjacent to the water being pumped. This limitation makes it necessary to provide a relatively large wind rotor for a given power capacity (i.e. the rated wind speed must be low) unless the site happens to be exceptionally windy.

With larger machines, in the range 10-100 kw. capacity, the choice of site is wider. They can be located on the best exposed site—preferably on a hilltop—and there is every encouragement to install wind-driven electric generators of medium voltage to obtain the advantage of efficient power transmission to a distance of a few hundred yards. Indeed, when the establishment of a new community in an underdeveloped area is being considered, the choice of its location might well be influenced by the adequacy of the wind régime for power production.

The selection of wind power sites appears to require skill, acquired by experience, but it can be stated with some confidence that sites on the summits of well-exposed, smoothly rounded hills generally give good results. The wind speed rises with altitude h even above a level plain (it is commonly accepted that wind speed is proportional to $h^{0.17}$) while suitably shaped hills appear to act as an aerofoil and to give some acceleration of the wind passing over their tops. Extensive wind surveys in Great Britain and Ireland [7] have shown that, in districts having annual mean wind speeds of 17.5, 15 and 12.5 m.p.h. (28, 24 and 20 km./h.), hilltops can be found where these speeds are respectively from 24-29 m.p.h. (38-46 km./h.), 19-25 m.p.h. (30-40 km./h.) and 17-26 m.p.h. (27-49 km./h.). The hills chosen range in height from about 400 ft. (120 m.) to 2,000 ft. (600 m.) and the highest hills are not always the most windy. An increase in annual mean wind speed of 50 per cent is thus commonly found in these survey areas but the sites concerned are all near to the coast. While there is already some evidence that similar effects will be found in other parts of the world, and in inland areas, more extensive surveys are needed to confirm this.

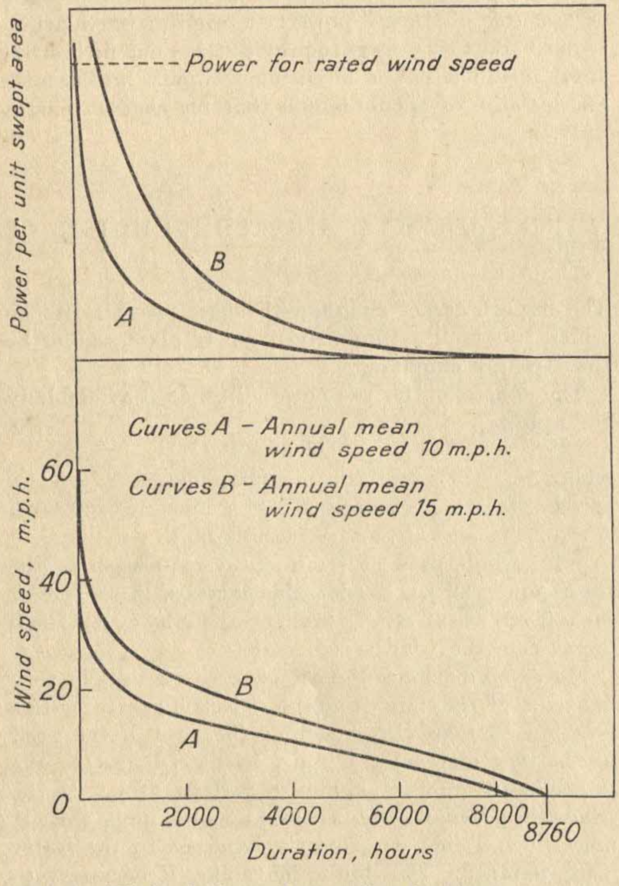

Fig. 1. Wind velocity and power-duration curves.

In a wind survey, cup anemometers are used because they are much cheaper, both in first cost and in installation, than those of the pressure tube type and are more easily operated by semi-skilled observers at a number of sites. For the British survey two forms of cup anemometer have been used: (a) counter instruments mounted on 10 ft. (30 m.) poles. These integrate the run-of-wind, in miles, and their simple cyclometer counter can be read, from ground level, by an untrained local observer; (b) electrical contact instruments, on 30 ft. (9 m.) masts, used with a chart recorder. The anemometer makes a contact, in a battery-operated circuit, after the passage of a predetermined run of wind and the clockwork-driven chart is marked with a dot for every 2 miles of wind. Thus, twice the number of spaces (between dots) in each hourly movement of the chart gives the hourly wind speed in m.p.h.

The counter anemometer enables only the mean wind speed to be determined for the period of time between readings while from the contact anemometer an annual velocity-duration curve can be drawn, as in the lower part of Fig. 1, after the hourly wind speeds have been extracted from the chart and grouped in order of magnitude.

The power-duration curve is plotted by cubing the ordinates of the velocity-duration curve and the upper curves in Fig. 1 show the increased power output obtained at a site with a mean wind speed of 15 m.p.h. as compared with that having a mean of only 10 m.p.h. For a given size of rotor the annual energy output is approximately proportional to the area bounded by the power curve and the horizontal line corresponding to full output for wind speeds above the rated value. The specific output, in kwh. per annum/kw., is obtained by determining this area for a given operating range of wind speeds. For arid areas which are not very windy an appropriate range would be a "cut-in" wind speed of 13 m.p.h. and a rated wind speed of 25 m.p.h. [7].

To ensure that the wind speeds measured at the site during the period of the observations do not lead to under- or over-estimation of the available energy, the results are compared with those for the same period obtained at the nearest established meteorological station having long-term records.

From examination of a large number of power-duration curves of widely-separated sites in Great Britain and other countries it has been found that there is a common relationship between the annual mean wind speed for a site and the estimated specific output from a machine, with a given operating range, located there. Measurement of the annual mean wind speed—by means of the simple counter anemometer—is thus sufficient for the purpose of estimating the energy potentialities of a site by interpolation of the specific output/mean wind speed curve. But the more detailed measurements from a recording instrument are needed, especially, to determine the duration of calm spells and of exceptionally high winds as well as the diurnal variations in wind speed which may have an important influence on the choice of loads to absorb the available power.

THE ECONOMIC DESIGN OF WIND-DRIVEN MACHINES

Although the number of individual designs for windmills which have been invented is legion, almost all can be placed in one of two classes—in the first class the axis of the working part (the rotor) is vertical and in the second it is horizontal.

Machines of the vertical axis type suffer from the general defects of slow running and low efficiency. Expensive gearing is needed to enable them to be used for driving electric generators which normally run at high speed, while an efficiency of little more than half that of the horizontal axis, propeller type, means that the rotor must be relatively large for a given power capacity. This type of design is not likely, therefore, to be followed commercially, especially for electric power generation. But, in considering the development of arid areas inhabited by primitive peoples who are unable to purchase costly machines, it may be that a simple water-pumping windmill, having a vertical wooden axle and woven mats for sails, could be made from locally available materials and with local labour. The low efficiency of a windmill is not, in itself, important; cheap and effective construction is the main criterion so that if simple machines of the type suggested here could be made to work satisfactorily they would, at least, serve to introduce wind power to peoples having no previous conception of the possibilities.

For power utilization on a fuller scale, however, there is no doubt that propeller-type windmills will be much more practicable and it is this type wich is being developed, with various modifications in detailed design, by the manufacturers interested in this subject.

Non-electric windmills for water pumping have slow-running, multi-bladed wheels developing a high starting torque and capable of producing some power in light winds. For the drive of electric generators, high-speed rotors having two or three blades are used. Small windmills, driving direct-current generators, rotate at a speed varying with the wind speed and have a governor, or wind-spilling device, to limit the power output in high winds. Larger machines, generating alternating current and connected to an adjacent network, must run at a constant speed determined by the network frequency. The blades may be of variable pitch controlled hydraulically or by flaps on the blades themselves. For medium-sized machines a satisfactory, and cheaper, construction [8] is to employ fixed-pitch blades (which can then be braced) and to use some form of air brake which comes into operation as the wind speed increases.

Discussion of the actual designs and construction details of wind-driven machines would be out of place here but it may be worth while to consider the economic effects of varying one of the main factors—the rated wind speed—according to the wind régime at the site for which the machine is intended.

To take a numerical example, consider a wind-driven generator of propeller diameter 12-15 metres and having a capacity of 50 kw. at a rated wind speed of 40 km./h. If, keeping the same rotor diameter, the rated wind speed were reduced to 32 km./h. the capacity would fall to $\frac{20^3}{25^3} \times 50 = 25.6$ kw. Taking the cost per kilowatt as \$340 in the first case, this would rise to something under \$340 $\times \frac{25^3}{20^3}$ per kw. in the second. (The total cost of the machine with the lower capacity would be reduced because of the smaller generator and its associated equipment.) Suppose it to be equivalent to \$560 per kw. Take annual charges as 12 per cent in each case. Table I compares the energy production and cost for the two machines. The figures for specific output in columns 2 and 5 have been taken from curves relating specific output with annual mean wind speed [5].

Annual mean wind speed at the site	*Rated wind speed 40 km./h.*			*Rated wind speed 32 km./h.*		
	Specific output	*Total annual output*	*Cost per kwh.*	*Specific output*	*Total annual output*	*Cost per kwh.*
m. per sec.	*kwh. p.a./kw*	*kwh.*	*cents*	*kwh. p.a./kw.*	*kwh.*	*cents*
4.4	1 050	52 500	3.84	1 900	48 600	3.53
5.5	1 900	95 000	2.12	3 000	76 800	2.24
6.6	2 700	135 000	1.49	3 800	97 300	1.77
7.7	3 500	175 000	1.15	4 700	120 300	1.43
8.8	4 250	212 500	0.95	5 350	137 000	1.26
9.9	4 800	240 000	0.84	5 800	148 500	1.15
11.0	5 350	267 500	0.75	6 200	159 000	1.08

The conclusions to be drawn from the figures in the table are as follows: (a) The cost of wind generated energy under these conditions is always lower than the fuel component of generating cost by diesel engine (about 4 cents per kwh.) when diesel fuel costs 9.5 cents per litre or more. It competes with the lowest diesel cost (about 1.10 cents per kwh.) at sites with high annual mean wind speeds. (b) Although the effect is less marked at sites with low mean wind speeds, a rated wind speed of 25 m.p.h. (40 km./h.) is generally preferable to the lower one of 20 m.p.h. (32 km./h.) both for energy cost and total energy production in the year. Better use is being made of the material in the rotor, tower and other parts of the machine when a larger generator is fitted. (c) When the rated wind speed is 20 m.p.h. (32 km./h.) the "cut-in" wind speed is about 10 m.p.h. (16 km./h.) as compared with, say, 13 m.p.h. (21 km./h.) with a rated speed of 25 m.p.h. (40 km./h.). As indicated by the much greater specific output for the lower wind range the second machine would be in operation for many more hours in the year although it would be giving a lower power output than the machine with the higher rated wind speed. This fact has importance when considering the provision to be made to cater for periods of low wind speed.

UTILIZATION OF WIND-GENERATED ENERGY

The energy costs indicated above are based, of course, on the assumption that all the energy generated by the wind throughout the year is fully utilized. If it were possible to provide storage without considerable expense and losses in conversion from one form to another, all the energy could be used without difficulty. The practical problem is to find outlets for the power as it occurs, at random times, with the minimum requirement for devices having no other purpose than storage.

Success in solving this problem depends upon the forms in which energy is required, at given times of the day, week or year, by the community to be served and also upon the arrangements made to switch over available power so that it can supply loads having inherent storage. To give examples, if a certain amount of power is required for electric lighting at specified times each day, the wind-generated energy for the purpose must be stored, in electrical form, i.e. in a battery of accumulators, to cater for the occasions when no wind blows at those times. But the battery capacity should be no greater than is absolutely necessary to store enough of the total energy for this purpose so that the minimum cost is incurred for the battery.

The remainder of the annual energy must be used by loads which can accept power usefully at any time or, at least, without severe time restrictions. Examples of such loads are (a) water pumping, for domestic supply and for irrigation; (b) space heating and cooking by thermal-storage types of equipment; (c) distillation of water; (d) refrigeration: and (e) mechanical processes such as the grinding of grain or other agricultural products, chopping and sawing.

A switching control system would be needed to ensure that after feeding, for a predetermined period, a load with a limited capacity, the power still being produced is passed on automatically to other loads which can absorb it. The annual output of over 100,000 kwh. from a 50 kw. wind-driven plant located at a site with an annual mean wind speed of some 13 or 14 m.p.h. (21 or 22 km./h.) might, in this way, supply most of the energy needs of a community of perhaps a hundred or more people, depending on their way of life [3, 4].

In arranging the loads to be connected to a wind power supply, regard should be paid to the fact that it must be possible to bring in, at any time, loads of total capacity equal to that of the wind power plant itself and thus to take full advantage of the periods when the wind is strong enough to give full power output from the plant.

In considering wind energy for arid or semi-arid areas it is assumed, throughout, that the intention is to utilize local sources of energy for development rather than to attempt—in the early stages at least—to bring in, from outside the area, power supplies in the form of oil fuel or of electric power by long distance transmission. Other local sources which might be used are solar radiation and, sometimes, waste vegetable matter. For the best economy it would be planned to use these sources in combination, each serving the purpose to which it is best suited at times when it becomes available [8]. Thus, for example, solar radiation could be combined with wind power for water heating, cooking, and distillation while waste material could be burnt to raise steam for a small steam engine (which is being developed in Great Britain) to supplement the wind power for various mechanical purposes.

As a result of the research and development work in several countries during the last few years, wind-driven machines, devices using solar radiation and equipment designed to make use of waste vegetable matter, either directly or through fermentation, have reached the stage of practical realization. It is now necessary to make experimental studies on their application, both singly and in combination, to the needs of communities.

One should not leave this question of utilization without mention of two forms of energy storage which have been suggested as possibilities in arid areas. These are hydrogen, and compressed air.

Hydrogen could be produced electrolytically from relatively small volumes of water (which must, however, be distilled) and stored in gas holders, preferably under compression [11]. It could then be used as a fuel, either for the simple purposes of cooking and heating or to drive an internal combustion engine. The idea is certainly attractive in that the result would be the supply of an effective fuel from even a very limited local supply of water. Unfortunately, its economy is doubtful mainly owing to the high cost of providing an adequate gas holder but partly also because of the power losses, and capital costs, involved in the several conversions of energy from electrical to chemical, then to thermal and finally to mechanical.

Although its possibilities for this purpose have not, to the writer's knowledge, been fully investigated, compressed air as a form of storage might prove more economical than hydrogen. A windmill could drive an air compressor either directly or electrically through the medium of an electric motor supplied from a wind-driven generator. A compressed air chamber would, of course, be needed, and this might be expensive to construct, but there could be fewer stages in the conversion of energy than in the case of hydrogen.

CONCLUSION

There are no fundamental reasons, economic or practical, against the use of wind energy as an agency in the development of many of the arid areas.

During the past six or seven years there has been widespread and rapidly increasing interest in the possibilities of using wind power on a significant scale for electricity production. Several countries have established officially sponsored wind power committees to be responsible for investigations on the subject and have started wind surveys. The total effort being made in this way, by manufacturers interested in the development of wind power plant and its associated equipment, is very considerable and, although work of this kind presents many technical problems, there is no reason to think that these will not be solved.

If full advantage is to be taken of this source of energy, however, attention should be given to the following points: (a) there should be more widespread diffusion of the knowledge of the possibilities in areas where both the climatic and economic conditions are known to be favourable; (b) wind surveys, of a systematic character, should be made in these areas and the information obtained should be made freely available as a guide to windmill designers; (c) it would be helpful to the manufacturers if an indication could be given of the possible demand for wind-driven plant in underdeveloped areas. Help is needed, also, in the creation of an actual demand. Probably this help can best be given through governmental or other official channels. Without it, development can only be through the individual initiative of manufacturers and may be a slow process depending, as it must, on the creation of demand through the normal forms of publicity. Such publicity is hardly likely to be effective among the peoples most concerned; actual observations of the plant in practical operation would appear to be the only realistic way to create a demand.

In conclusion the writer would like to emphasize most strongly the need for international co-operation in establishing a few experimental schemes at well-selected places distributed over the arid zones of the world. Each scheme should take the form of an installation of all the appropriate forms of power plants and load equipment which are available to utilize only the local sources of energy—wind, sunshine and waste material—in combination to supply all the energy needs of a small community.

Careful planning and supervision would be needed to ensure, with the collaboration of the inhabitants, full utilization of the available energy from all the local sources.

The results of such experiments would certainly provide a much more effective basis for development through the applications of energy in arid zones than any quantity of discussion.

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L'UTILISATION ÉCONOMIQUE DE L'ÉNERGIE ÉOLIENNE DANS LES RÉGIONS ARIDES

par

E. W. Golding

RÉSUMÉ

Bien que le vent puisse fournir chaque année de grandes quantités d'énergie dans maintes régions qui en ont grand besoin pour leur mise en valeur, on a peu utilisé jusqu'ici l'énergie éolienne. Certes, il y a un nombre considérable d'appareils à pomper l'eau ou "éoliennes" et quelques petits groupes électrogènes mus par le vent dans les régions où de telles machines sont particulièrement nécessaires, mais leur production annuelle ne représente au total qu'une faible partie de l'énergie dont on pourrait tirer parti à bon compte.

Les principales raisons pour lesquelles on a apparemment négligé cette source d'énergie, accessible à tous et inépuisable, sont probablement les suivantes :

1. Jusqu'à une époque récente, les constructeurs d' "éoliennes" ne se sont pas suffisamment intéressés à la mise au point de machines capables de produire de l'énergie en grandes quantités.
2. Les habitants des régions que ce problème touche le plus directement ne se rendent pas encore bien compte des possibilités qu'offre l'énergie éolienne, et les études systématiques sur le vent, qui permettraient de déterminer les emplacements les plus favorables à l'utilisation de cette énergie, restent à faire.
3. Le vent est une source d'énergie sur laquelle on peut compter bon an mal an, mais il ne faut pas lui demander de fournir telle ou telle puissance à n'importe quel moment. Les dispositifs servant uniquement à emmagasiner de l'énergie sont coûteux; aussi l'énergie éolienne ne peut-elle être utilisée à bon compte que si elle est intégralement consommée au fur et à mesure de sa production.

Si les possibilités d'utilisation de l'énergie éolienne sont mal appréciées, c'est que l'on croit généralement — par manque d'informations — que cette solution est à écarter quand on ne peut pas constamment compter sur un vent régulier. Mais on peut aborder la question de façon plus réaliste en se demandant à combien reviendrait l'énergie produite par d'autres méthodes dans des régions écartées comme il s'en trouve par exemple dans les contrées arides. Bien entendu, un moteur à huile lourde, par exemple, a l'avantage de pouvoir fournir de l'énergie à tout moment, à condition d'être régulièrement approvisionné en gas-oil et convenablement entretenu. Mais le prix de revient du kilowatt-heure produit par ce moyen est souvent élevé en raison de l'importance des frais de transport. Par exemple, si le combustible coûte 0,10 dollar le litre (ce qui n'est nullement rare), il entre ensuite pour plus de 0,035 dollar dans le prix du kilowatt-heure d'énergie.

Le prix de revient de l'énergie tirée du vent dépend : *a*) de la production spécifique annuelle T_s à l'emplacement de l'installation ; *b*) du capital investi dans l'installation, soit C livres et *c*) du taux (p %) des frais annuels (intérêts, amortissement et frais d'entretien, ces derniers représentant environ 1 ou 2 % du capital investi).

Le prix de revient de l'énergie peut donc s'exprimer par la formule suivante :

Prix de revient du kilowatt-heure en pence $= \frac{pC}{T_s}$.

Pour des génératrices éoliennes de puissance moyenne (entre 10 et 100 kW) le montant de l'investissement sera vraisemblablement compris entre 300 et 450 dollars par kilowatt (sans batterie d'accumulateurs). Si donc nous prenons $C = 350$ dollars, $p = 12$ % et $T_s = 2.500$ kWh par an et par kilowatt, le prix de revient du kilowatt s'établit à

$$\frac{12 \times 350}{2.500} = 1{,}68 \text{ cent.}$$

La comparaison avec le prix de revient de l'énergie fournie par des moteurs à huile lourde est donc très favorable à l'éolienne, mais il faut bien voir que ce chiffre n'est valable que si la totalité de l'énergie produite par le vent au cours de l'année est effectivement utilisée sans qu'on ait recours à des batteries d'accumulateurs.

Il est clair qu'avant de pouvoir tirer pleinement parti de l'énergie éolienne il faudra mener des recherches dans trois directions. Elles porteront sur la construction de bonnes machines d'un prix de revient au kilowatt relativement modique, sur le choix des emplacements favorables et sur l'établissement de plans de charge permettant de tirer pleinement parti d'une production d'énergie irrégulière. C'est au constructeur qu'il appartient de réaliser les machines et l'équipement de distribution nécessaire, mais l'utilisateur éventuel — ou parfois un organisme agissant en son nom — doit aider l'ingénieur chargé d'établir les plans de la machine, en lui fournissant des données anémométriques permettant de calculer de façon approchée les productions d'énergie ; il devra aussi prévoir un plan de charge adapté aux besoins énergétiques locaux.

L'installation d'un groupe électrogène éolien doit nécessairement être précédée d'études systématiques sur les vents, comportant des mesures anémométriques effectuées en un certain nombre d'emplacements possibles. En général, les meilleurs emplacements se trouvent sur des hauteurs où l'on bénéficie de la vitesse plus grande du vent ; en outre, si ces hauteurs ont l'exposition et le profil voulus, le vent accélère son mouvement au passage de leur sommet.

L'énergie que recèle le vent est donnée par la formule : $P = 0{,}0006\ AV^3$ dans laquelle P représente la puissance du vent en kW, A la surface balayée en mètres carrés, et V la vitesse du vent en mètres/seconde.

Pour une roue éolienne de dimensions données, la quantité d'énergie captée dépend donc en grande partie de la vitesse du vent V.

Les études faites en Grande-Bretagne montrent que la vitesse moyenne annuelle du vent à de bons emplacements est de 50 à 100 % plus forte que dans les environs immédiats.

La production spécifique (en kilowatt-heure par an et par kilowatt) est estimée à partir de la courbe puissance-durée à l'emplacement de l'installation en fixant les valeurs limites de la vitesse du vent entre lesquelles travaillera l'éolienne. Cette courbe est elle-même déduite de la courbe vitesse-durée correspondant au régime du vent.

On a heureusement constaté que le régime du vent semble varier si peu d'un emplacement à un autre (dans la gamme des vitesses où travaille normalement l'éolienne) qu'il suffit de connaître la vitesse moyenne annuelle du vent à l'emplacement considéré pour obtenir la production spécifique, au moyen d'une courbe production spécifique/vitesse moyenne du vent. Cela simplifie grandement l'étude systématique du vent en réduisant le matériel et le personnel nécessaires. Toutefois, la mesure de la vitesse moyenne du vent ne suffit pas pour renseigner sur la fréquence des vents, le temps pendant lequel ils soufflent, les périodes de calme et celles de grand vent.

Il est deux principaux types de machines aéromotrices : le type à arbre vertical, qui est lent et d'un mauvais rendement, et le type à arbre horizontal, dont le rotor est en forme d'hélice. Équipé d'une hélice à deux ou trois pales, le second est plus apte aux grandes vitesses et d'un haut rendement. Les éoliennes à pales multiples, qui ont un couple de démarrage élevé et peuvent fonctionner par un vent de faible vitesse, servent uniquement au pompage de l'eau.

Une éolienne à axe vertical, bien qu'offrant l'avantage de pouvoir utiliser le vent d'où qu'il vienne sans être orientée, demandera vraisemblablement une mise de fonds deux fois plus forte qu'une éolienne à hélices de même puissance. Cependant, il serait peut-être possible, en se servant de matériaux disponibles sur place, par exemple de nattes de roseaux pour la voilure, de construire à très bon compte un type simplifié d'éolienne à arbre vertical et de faible puissance. Dans les premières phases de la mise en valeur d'une région où l'argent est plutôt rare, une telle machine pourrait avoir l'avantage de prouver aux habitants qu'on peut tirer parti de l'énergie du vent.

Le choix de la vitesse nominale du vent (c'est-à-dire de la vitesse minima pour laquelle un aéromoteur donne sa puissance nominale), d'après la connaissance que l'on a du régime des vents à l'emplacement considéré, est une des principales questions que doit trancher l'ingénieur en établissant les plans d'une éolienne.

Par exemple, si dans le cas d'un rotor d'un diamètre constant d'environ 15 mètres on considère des vents nominaux de 40 et 32 kilomètres à l'heure, on constate que le kilowatt installé revient à 340 dollars pour un vent nominal de 40 kilomètres à l'heure et à 560 dollars pour un vent nominal de 32 kilomètres à l'heure. En admettant que les dépenses d'exploitation annuelles soient de 12 % du capital investi, le prix de revient du kilowatt/heure d'énergie variera comme le montre le tableau ci-après en fonction de la vitesse moyenne annuelle du vent à différents emplacements.

Dans ces conditions, le vent nominal le plus fort est aussi le plus économique, mais le plus faible aurait l'avantage de permettre à l'éolienne de fonctionner un plus grand nombre d'heures par an.

Si l'on passe à la question de l'utilisation de l'énergie ainsi tirée du vent, on constate qu'une machine de 50 kW, installée à un emplacement où la vitesse moyenne du vent est de 21 ou 22 kilomètres à l'heure, pourrait fournir la presque totalité de l'énergie nécessaire à une collectivité d'une centaine de personnes, ou même davantage selon leur genre de vie. Mais, pour pouvoir se passer de dispositifs coûteux dont le seul usage est d'emmagasiner l'énergie, il faudra se servir de l'énergie produite à des fins comportant du stockage, par exemple pour pomper ou chauffer de l'eau, chauffer des locaux et des appareils de cuisine au moyen d'appareils thermiques à accumulation, pour faire fonctionner des alambics, des réfrigérateurs, des broyeurs ou des hache-paille.

Il sera nécessaire d'établir un plan de charges pour que l'énergie éolienne disponible soit utilisée au mieux, grâce à un dispositif de commutation automatique permettant de passer d'une charge à une autre. Il faudra adapter cette technique aux conditions de vie des différentes collectivités.

On dispose évidemment d'une grande latitude pour combiner l'énergie éolienne avec d'autres sources locales d'énergie, par exemple le rayonnement solaire et celle que l'on peut tirer des déchets végétaux.

En conclusion on ne saurait trop insister sur la nécessité d'installer le plus tôt possible un certain nombre de centrales expérimentales si l'on veut faire

Vitesse moyenne annuelle du vent envisagé à l'emplacement	*Vent nominal de 40 km à l'heure*			*Vent nominal de 32 km à l'heure*		
	Production spécifique	*Production annuelle globale*	*Prix de revient au kW*	*Production spécifique*	*Production annuelle globale*	*Prix de revient au kW*
km/h	kWh/an/kW	kWh	en cents	kWh/an/kW	kWh	en cents
4,4	1 050	52 500	3,84	1 900	48 600	3,53
5,5	1 900	95 000	2,12	3 000	76 800	2,24
6,6	2 700	135 000	1,49	3 800	97 300	1,77
7,7	3 500	175 000	1,15	4 700	120 300	1,43
8,8	4 250	212 500	0,95	5 350	137 000	1,26
9,9	4 800	240 000	0,84	5 800	148 500	1,15
11,0	5 350	267 500	0,75	6 200	159 000	1,08

de réels progrès dans l'utilisation des ressources locales d'énergie pour la mise en valeur des régions arides.

Il faudra prévoir plusieurs installations, largement dispersées dans les régions arides. Chacune devra être équipée de tous les types de génératrices et d'équipement existant actuellement pour l'exploitation de l'énergie éolienne ou du rayonnement solaire et l'utilisation des déchets végétaux comme combustible ; ce matériel devra être utilisé à plein rendement pour pourvoir à la totalité des besoins énergétiques de la collectivité locale. Sous la direction de spécialistes compétents et avec la collaboration des intéressés, seront déterminées les meilleures méthodes de combinaison des différentes sources d'énergie et les résultats obtenus seront largement diffusés ; pour cela, on ne saurait s'en remettre aux constructeurs, qui n'ont en effet aucun moyen, en dehors des voies publicitaires normales, de faire connaître aux intéressés les possibilités de ce genre.

Ces méthodes sont très insuffisantes en l'occurrence ; le matériel ne sera guère utilisé que pour des démonstrations pratiques de ses possibilités, mais des expériences combinées comme celles que nous suggérons ne sont pas du ressort des constructeurs.

LA UTILIZACIÓN ECONÓMICA DE LA ENERGÍA EÓLICA EN LAS REGIONES ÁRIDAS

por

E. W. GOLDING

RESUMEN

Hasta hoy se ha hecho escaso uso del enorme potencial de energía eólica que podría explotarse en beneficio de ciertas regiones, para cuyo desarrollo económico la fuerza motriz es una necesidad primordial. Cierto es que en algunas partes donde son especialmente necesarios, se ven molinos elevadores de agua y generadores eléctricos movidos por el viento ; pero la producción energética anual de tales aparatos es sólo una fracción mínima del potencial que pudiera explotarse económicamente.

Las razones que explican este abandono en que se tiene a una fuente de energía tan inextinguible y fácilmente asequible son, con toda probabilidad, las siguientes:

1. Hasta muy recientemente, los fabricantes de tales aparatos no han prestado mayor atención a la manufactura de tipos utilizables en más amplia escala.
2. Los habitantes de las regiones en que con más eficacia pudieran usarse estos métodos no aprecian suficientemente las posibilidades de la energía eólica. Por consiguiente, no se han llevado a cabo los estudios eolográficos necesarios para determinar los puntos óptimos de emplazamiento.
3. Si bien el viento es una fuente segura de energía

anual, no ofrece la certeza de suministrar fuerza motriz utilizable en un momento dado. Todo aparato destinado exclusivamente a acumular energía es costoso; un mecanismo eólico económico exige la utilización inmediata y total de la fuerza generada por el viento en cualquier momento en que éste sople.

El desconocimiento de las posibilidades de generación de fuerza de origen eólico se basa en el error general de creer que tal sistema de producción de fuerza es inaplicable a menos que sople un viento continuo. Un enfoque más realista de este problema consistiría en calcular el costo de la producción de energía por otros métodos en regiones remotas, como las llamadas zonas áridas. Es generalmente sabido que un motor de explosión tiene la ventaja de que puede producir la fuerza motriz necesaria en el momento mismo en que se necesita siempre que se disponga del combustible necesario y que el motor se mantenga en buenas condiciones. Sin embargo, el costo por kilovatio-hora de la energía así producida es a menudo muy elevado, debido a los considerables gastos de transporte. Por ejemplo, cuando el precio del combustible es de 0,10 dólares por litro (lo cual no es excepcional), la proporción del costo por kilovatio-hora producido alcanza a 0,035 dólares.

El costo de producción de energía depende de: *a*) el rendimiento específico en el lugar de la instalación (T_s); *b*) el precio inicial del aparato generador (C dólares y *c*) las cargas nuales por interés del capital y depreciación (*p* %) [incluyendo un gasto de mantenimiento equivalente al 1 o 2 % del capital inicial].

El costo de producción de la energía puede por lo tanto expresarse así:

Costo por kilovatio-hora en centavos de dólar $= \frac{pC}{T_s}$.

El capital necesario para la instalación de un generador de energía de tamaño medio (entre 10 y 100 kilovatios) varía entre 300 y 450 dólares aproximadamente (sin acumuladores). Por consiguiente, si consideramos $C = 350$, $p = 12\ \%$ y $T_s = 2500$ kilovatio-hora por año por kilovatio el costo de producción será:

$\frac{12 \times 350}{2500} = 1{,}68$ centavos de dólar. Es ésta una cifra bastante baja en comparación con el costo de la energía producida por un motor de explosión, pero hay que tener en cuenta que en ese cálculo se supone la utilización de toda la fuerza producida a lo largo del año, sin hacer uso de acumuladores.

Resulta evidente que para que la energía eólica pueda ser explotada plenamente es preciso realizar investigaciones en tres direcciones distintas: sobre la construcción de aparatos generadores de bajo costo de funcionamiento por kilovatio-hora; la selección de emplazamientos favorables y un apropiado esquema de utilización que permita hacer uso de la fuerza en cualquier momento en que ésta se produzca. Al fabricante de los aparatos corresponde resolver todos los problemas relacionados con la construcción de los mismos y de los mecanismos de trabajo, pero el futuro consumidor —o, mejor aún, una organización que lo represente— debe suministrar al fabricante todos los datos eolográficos que puedan ser útiles para la construcción de las máquinas y servir de base para el cálculo de la producción energética, y preparar un plan de distribución de la carga que corresponda a las necesidades de fuerza consumible sentidas en la localidad.

Como fase preliminar a la instalación de plantas de aprovechamiento de la energía eólica es imprescindible realizar estudios eolográficos en un número de posibles emplazamientos. En general, las cimas de cerros y colinas son los más favorables, ya que su altura misma, sobre todo si se hallan bien situados y conformados, sirve para incrementar la velocidad del viento sobre la cima.

La fórmula que determina la fuerza del viento es; $P = 0{,}0006\ AV^3$ donde P representa la fuerza del viento en kilovatios, A el área (en m^2) sometida a la presión del viento, y V la velocidad del viento (en m/s).

Por lo tanto, para un rotor de un tamaño dado, la fuerza depende de la velocidad del viento (V).

En los índices anuales de la velocidad media del viento observada en buenos emplazamientos, dicha velocidad resulta de un 50 a un 100 % mayor que en los terrenos circundantes.

El cálculo de la producción específica (en kilovatios-hora por año por kilovatio) se obtiene de la curva de fuerza-duración referente a determinado emplazamiento y a una escala de velocidades dadas. Esta curva resulta a su vez de la curva del régimen de vientos (velocidad-duración).

Por fortuna, se ha hallado que los regímenes de vientos de diversos emplazamientos tienen carácter tan similar (dentro de la escala normal de funcionamiento de los aeromotores) que, si se conoce tan sólo la velocidad media anual del viento, puede calcularse la producción específica gracias a una curva de producción específica-velocidad media del viento. Esto facilita grandemente las labores de determinación eolográfica. Sin embargo, las medidas de la velocidad media del viento no son suficientes para conocer la proporción y duración respectivas de los períodos de calma y de los vendavales.

Hay dos tipos principales de aparatos movidos por el viento: el de eje vertical que se caracteriza por su baja eficiencia y lenta velocidad, y el de eje horizontal, con un rotor en forma de hélice. Éste es el más conveniente —con una hélice de dos o tres palas— para un funcionamiento a altas velocidades y gran rendimiento. Las ruedas de paletas con un momento de torsión inicial muy elevado, que pueden funcionar con un viento poco veloz, se usan únicamente como elevadores de agua.

El aeromotor de eje vertical, aunque posee la ventaja de poder utilizar el viento procedente de todas direcciones sin necesidad de orientación, supone por lo general una inversión de capital por lo menos doble de la necesaria para un aeromotor de hélice de idéntica capacidad. Sin embargo, es posible que llegue a construirse económicamente un tipo simple de aeromotor de eje vertical de bajo rendimiento, haciendo uso de materiales de producción local, por ejemplo las esteras de juncos para las aspas. Durante las primeras fases del desarrollo de una región de escasos recursos monetarios, tales artilugios pueden muy bien cumplir la función de introducir el principio de la utilización de la energía eólica.

Importante cuestión que debe decidir el constructor del aparato basándose en los datos referentes al régimen de vientos es la determinación de la velocidad óptima (es decir: la velocidad del viento a la que la máquina produce su máximo rendimiento).

Así, calculando a base de un rotor de un diámetro fijo de unos 15 metros, el costo inicial tomando como velocidad óptima de 11 m/seg sería de 340 dólares, mientras que con una velocidad óptima de 9,9 m/seg sería de 560 dólares. Si calculamos que el costo anual alcanza el 12 %, el costo por kilovatio-hora de energía producida variará en los casos de emplazamientos con diferentes velocidades medias anuales según se indica en la tabla siguiente:

Velocidad media anual en el lugar de emplazamiento	*Velocidad óptima: 11 m/seg*			*Velocidad óptima: 9 m/seg.*		
	Rendimiento específico	*Rendimiento total anual*	*Costo por kW*	*Rendimiento específico*	*Rendimiento total anual*	*Costo por kWh*
en m/seg	kWh. p.a./kW	kWh	cents. de dólar	kWh. p.a./kW	kWh	cents. de dólar
4,4	1 050	52 500	3,84	1 900	48 600	3,53
5,5	1 900	95 000	2,12	3 000	76 800	2,24
6,6	2 700	135 000	1,49	3 800	97 300	1,77
7,7	3 500	175 000	1,15	4 700	120 300	1,43
8,8	4 250	212 500	0,95	5 350	137 000	1,26
9,9	4 800	240 000	0,84	5 800	148 500	1,15
11,0	5 350	267 500	0,75	6 200	159 000	1,08

En tales circunstancias, la velocidad optima más elevada es la más económica, aunque en el caso de la velocidad más baja existe la ventaja de que el molino funcionará durante un número mayor de horas a lo largo del año.

Estudiemos ahora la cuestión del empleo de la energía generada por el viento. Un aparato de 50 kW emplazado en un lugar que disponga de una velocidad anual media de 6 a 6,5 m/seg. producirá toda o la mayor parte de la fuerza que necesita una comunidad de un centenar o más de personas, según su modo de vida. Pero para evitar la instalación de costosos acumuladores será necesario utilizar la fuerza con fines que en sí mismos entrañen una acumulación de energía: bombeo de agua, calentamiento de agua, calefacción y cocinas de sistema de conservación térmica, destilación, refrigeración y molienda o picado de productos alimenticios.

Será por lo tanto necesario establecer un sistema de conmutadores automáticos que dirijan la fuerza libre de un trabajo a otro de la manera más ventajosa. Estos sistemas tendrán que adaptarse naturalmente a las distintas condiciones reinantes en las diferentes comunidades. Es innegable que existen grandes posibilidades en la combinación de la energía de origen eólico y otras fuentes de fuerza motriz tales como la radiación solar y la combustión de substancias vegetales de desecho.

En conclusión, si se quiere fomentar el desarrollo de las zonas áridas, nunca se insistirá bastante en la necesidad de establecer lo antes posible instalaciones experimentales de utilización de la energía que pueda obtenerse localmente.

Para ello debieran establecerse varias centrales ampliamente distribuídas en las zonas áridas. En esas centrales deben instalarse modelos de todos los aparatos y maquinaria disponibles para la utilización de la energía eólica, de la radiación solar y de los productos de desecho, suministrándose a base de dichas fuentes la fuerza motriz necesaria para el consumo de la comunidad. Esas centrales, bajo la supervisión de los expertos y con el concurso de los habitantes de la región, podrán suministrar los datos necesarios para determinar los procedimientos más apropiados de utilización conjunta de las diversas fuentes de energía, debiendo hacerse después públicos los resultados así obtenidos. Las medidas de este género no deben dejarse en manos de los fabricantes, quienes sólo disponen de los procedimientos normales de publicidad para dar a conocer tales posibilidades a los medios interesados.

Un método tal sería totalmente inadecuado en este caso: el empleo de máquinas y aparatos para la utilización de la energía sólo puede llegar a tener amplia aplicación merced a un sistema combinado de demostraciones de sus ventajas, lo cual queda fuera de las posibilidades de los fabricantes.

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DISCUSSION

Mr. Pirie. It is important that while progress is being made in one direction, progress in the other directions should not remain static. Mr. Golding seems to foresee great developments in engineering while plant breeding, agricultural techniques and biochemistry remain the same. It is likely that plants could be developed that would be more economical with water, so that there would be much more abundant supplies of vegetable matter. It is not efficient to burn vegetation in an engine, and fermentation to produce alcohol is not wholly satisfactory because of the difficulty of distilling the alcohol. It would be better to use fermentations that produce methane. This has also the merit of conserving the N and P of the crop so that much, even if not all, the value of the vegetation as a compost is retained. It would be better still to investigate fermentations that produce water-insoluble, solid or liquid carbon compounds so as to avoid both the difficulty of distillation and that of storage.

N. Venkatesan. The comparison of costs between wind power and diesel power is interesting. Taking the maximum figure of $450/kw., and converting the costs to Indian currency, we get roughly 1 ¼ annas/unit as the cost of wind power. The average cost of generation with diesel plants in India is about 4 annas/unit. Therefore, wind power is certainly economical. Mr. Siddiqui raised the question of the comparative cost of hydropower. For comparison with cost of wind power in a rural area, we must consider the cost at an 11 kw. distribution point. This may be about 1 anna or 1 ½ annas per unit. We are unable to extend transmission lines to rural areas, as it is uneconomical.

Regarding the design of windmill plants, with the conventional type of propeller plant, it is not possible to regulate the output to suit the load demands. With the new type of windmill mentioned by Mr. Golding, would it be possible to have some sort of governing device as in a steam or hydraulic prime mover?

Regarding the type of generating plant, if a synchronous alternator is used, what is the method of maintaining constant speed to maintain constant frequency? This difficulty would be avoided if an induction alternator were used. As we all know, an induction machine, when driven above synchronous speed, acts as a generator and it requires no synchronizing equipment.

SOME PROBLEMS IN THE UTILIZATION OF WIND POWER IN INDIA

by

R. V. Ramiah

EARLY EXPERIMENTS IN MADRAS

Alfred Chatterton, Professor of Engineering in Madras, conducted some experiments in 1902 on the use of a windmill for raising water for irrigation. The following were his main findings: (a) A 16 ft. diameter windmill, placed 70 ft. above ground level could irrigate about 10 acres in Madras. (b) February and October were least windy. During May, June and July winds were strongest and sufficient water could be raised for irrigation. (c) A 16 ft. windmill gave the following output of water raised to a height of 25 ft.:

	Gallons
January	15 920
February	12 070
March.	17 318
April	24 140
May	30 450
June	29 215
July	25 380
August	21 180
September. . . .	18 020
October	12 240
November	19 600
December	22 740

Chatterton also calculated that a 12 ft. wheel could develop 0.207 h.p. in a wind of 10 m.p.h. He estimated that a windmill could develop about 60 per cent more power at Bangalore than at Madras. He also developed a method by which estimates can be made of h.p. and output of a windmill when wind data for a particular place were available. Chatterton concluded that windmills may not be as useful in the north of India as in the south. He particularly recommended the coastal areas of south India for siting windmills.

WINDMILL TRIALS IN MYSORE

The Mysore Department of Agriculture set up a windmill at Hebbal near Bangalore in 1936. The mill was of 40 ft. diameter and 50 ft. above ground level. The conclusions arrived at after carrying out trials were that a reservoir or tank should be built at ground level to collect and store the water during the windy hours, and that windmills were not suitable for irrigation though they could be used for domestic water supply.

The results of these experiments were that a windmill would not lift sufficient water in the months of January, February and March, when there is need for irrigation water. Fairly high wind velocities exist during the monsoon season, when the rainfall is sufficient for irrigation purposes. The mill does useful work only in a wind velocity of 6 m.p.h. and over. The conclusion was that windmills could be used for supplying water for kitchen gardens, domestic use and cattle farms where the requirement of water is small. Even in such cases, a storage tank at the ground level is desirable.

Some experiments on designing windmills to run on smaller wind velocities were conducted by the Department of Industry, Mysore, and actual field trials were made in some parts of the state. The mills were found useful only for domestic water supply.

WINDMILL IN COIMBATORE

The Madras Department of Agriculture set up a windmill at Coimbatore and collected some data from 1929 onwards. The mill was of 12 ft. diameter and placed 40 ft. above ground level. The same mill was moved to other places, such as Nellore and Guntur for carrying out trials. On the basis of the trials carried out, the following conclusions were arrived at: (a) The average maximum daily pumpage was 13,280 gallons in June (1933) and the average minimum daily pumpage was 1,453 gallons in April. (b) As the windmill did not provide sufficient water for irrigation, water lifted by the indigenous methods was used as a supplement. (c) The windmill supplied enough water for the staff quarters and the cattle. (d) During the monsoon, when irrigation from wells was not required, wind velocity was high. During the dry months when the crops actually required irrigation from wells, the wind was calm. (e) The usefulness of the windmill could be increased to some extent by building storage tanks at ground level.

PERFORMANCE OF WINDMILL IN POONA

In 1952, J. M. Sill published the performance data of a windmill installed at the observatory in Poona. His findings were as follows: (a) the windmill plant is not very efficient; (b) its use is limited to places where there is plenty of wind; (c) its power cannot be regulated, nor is it dependable; and (d) the windmill is an extremely useful machine in out-of-the-way places where electricity is not available.

Mr. Sill also indicated a method of calculating the theoretical h.p. that can be developed by a windmill

RESULTS OF WINDMILL EXPERIMENTS IN THE PAST

From experimental data available on the performance of windmills in India, the following conclusions can be drawn: (a) Favourable wind velocities do not coincide with the seasons of high water demand for crop irrigation in Poona, Meerut, Coimbatore, Madras and Bangalore. (b) A better use of wind power is to use windmills to lift water to storage tanks situated at ground level. (c) In no place and during no season is a windmill capable of fully supplementing natural rainfall to fulfil irrigation requirements.

SOME RECENT INVESTIGATIONS

During 1949 some proposals were made by the irrigation adviser to the Government of India for conducting experiments on windmills, and the following 12 places were selected by a committee of experts for the installation of windmills: Allahabad, Ahmedabad, Rajkot, Bhuj, Pusa, Bombay, Poona, Belgaum, Malegaum, Coimbatore, Trichinopolly and Vizagpatam.

Beyond this proposal no field work seems to have been carried out. Meanwhile, the Indian Meteorological Department issued three useful publications on wind power. The following in particular are of interest: (a) *Energy available for windmills in India*, by K. L. Bhatia; (b) *Measurement of wind for a wind power survey in India*, by S. P. Venkiteswaran; (c) *Wind data for windmills*, by Doraiswamy Iyer.

AN ANALYSIS OF THE PROBLEM

There are two important uses to which wind power can be put in India. They are (a) for lifting water for irrigation and (b) for generating electricity on a small scale, as required by farm houses, estates, tea and coffee plantations, etc. Utilization of windmills for grinding corn should also be kept in mind. A windmill was put to novel use in Coimbatore, for scaring birds during the harvest season, but it was not a success, as the birds got used to the periodical noises produced by the windmill.

TILLAGE PRACTICES AND MOISTURE CONSERVATION

The variation in wind velocity from month to month and the rather low wind velocities when water is particularly needed for irrigation are the two major factors which prevent the use of wind power for irrigation purposes.

Nearly 80 per cent of our cultivated land depends on rainfall for raising crops and this area does not receive rain when it is most needed. There are, however, places where a crop can be produced with less than the ideal amount of water. The crop yield may not be as good as under irrigated conditions, but it is better than not raising any crop at all. Another important factor should be kept in mind. It is not only the quantity of water that is supplied that is important but the time of its supply. Irrigation of crops at certain stages of growth is more important than at other stages. For example, an irrigation of 4 in. in depth for wheat or bajra at the flowering and grain formation stages is more valuable in producing high yields than at other stages of growth.

Certain tillage practices such as seed bed preparation, weeding, harrowing, etc., also lead to retention of soil moisture, thus facilitating crop growth.

The above mentioned facts lead to one conclusion. The windmill as a source of irrigation water cannot be dispensed with by the mere fact that it fails to supply all the supplemental water needed for crop growth. In some places it may enable one or two irrigations to be made, when the winds are favourable and at the required period to assist crop growth.

Crop practices and crop rotations are also changing in India, either owing to the demand for particular crops or as a result of introduction of cash crops. Keeping the availability of favourable wind velocities in view, new varieties of crops may be introduced in an area which can utilize the water whenever it becomes available.

SELECTION OF PLACES FOR EXPERIMENTS ON WINDMILLS

In selecting a place for installation and trial of a windmill for lifting water, the following practical and theoretical considerations should be kept in view:

(a) A careful study should be made of the availability and amount of wind power during a season and of whether this synchronizes with the demand for irrigation as a supplement to rainfall. (b) The windmill should be recommended only for rain fed areas where rainfall is neither adequate nor timely. (c) Places where even a small quantity of water is likely to aid crop production to a substantial extent should be selected. (d) Windmills should not be chosen for crops whose water requirements are high, such as paddy and sugar cane.

ESTIMATED POWER DEVELOPED OR WATER LIFTED BY A WINDMILL

A theoretical method can be developed for determining the amount of water that can be raised at different times of the year by a windmill of known dimensions and type, fixed at a given height above ground level, Fig. 1[1] shows the natural rainfall in Delhi during 1952 and average wind velocities in m.p.h. These two graphs indicate that maximum wind velocities occur in the months of June and July, and maximum rainfall occurs in the month of August. Supplemental irrigation is needed in the months of January, February, March, July, August and September, as indicated in Fig. 1.[1] This irrigation requirement is based on wheat as the winter crop and bajra as the summer crop in the Delhi area.

Bhatia has developed a method for determining the h.p. developed by a windmill based on the following equation:

$$\text{h.p.} = 1{,}001\ D^2V^3E \times 10^{-6}$$

where D = diameter of the windmill in ft.; V = velocity in ft./sec.; E = mechanical efficiency.

Given the height to which water should be raised, it is possible to calculate the amount of water lifted for a given wind velocity.

In Fig. 2[1] is shown wind velocity in m.p.h. and its cube plotted on a calendar graph of 12 months. By multiplying the cube of the velocity by a co-efficient, it should be possible to assess the amount of irrigation water to be lifted by a given windmill in any locality.

WIND POWER COMPLEMENTARY TO BULLOCK POWER

We have up to now considered that the windmill should be used only as an alternative source for the supply of supplemental irrigation water in a rain fed area. If we examine this principle in the light of the conditions existing in India, it requires modification. In some parts of the rain fed areas, bullocks are generally used for lifting irrigation water by Persian wheels, *charas* or *mhote*. The difficulty with the windmill in India is that it prevents the water of the well on which it is installed from being tapped by other means, and the pump of the windmill is such that it cannot be operated by a pair of bullocks. Because of the present design of the tower of the windmill, it is hardly possible to install a Persian wheel or *charas* on the same well. By redesigning the tower or substituting a single pole for it, however, it is likely that it will be possible to do so.

The present water lifting appliances used in India, such as the Persian wheel and *charas*, can only be driven by bullocks. We might now examine whether it is possible to develop a pump which can be either operated by a single bullock, a pair of bullocks or by a windmill, on the same installation.

INDIGENOUS WATER LIFTS OF INDIA

Experiments have been conducted on the output and efficiency of the indigenous water lifts of India. The mechanical efficiency of the Persian wheel is 32-39 per cent. The *charas* or the leather bucket *mhote*, which is less common than the Persian wheel, is about 49.2-53.5 per cent efficient. The output of Persian wheels and *charas* is above 3,500 gallons per hour and reaches about 7,500 gallons per hour at smaller lifts. For a lift of 20 to 30 ft. the output is about 5,000 to 5,500 gallons per hour. With such equipment and a pair of bullocks, which are used for other farm operations and transport also, the farmers in Punjab and the United Provinces lift enough water to supply 10 to 15 acres of land with supplemental irrigation. These figures may be taken as indications of the expected yields of windmills during minimum wind seasons. However, the indigenous water lifts of India are not designed to be driven by other mechanical means. This leads to the problem of developing a pump which can be driven either by a windmill or by a pair of bullocks.

DEVELOPMENT OF PUMPS OPERATED BY BULLOCKS

Some work has been done for the past few years in India on the design and development of pumps operated by bullocks. The Department of Industries, Madras, designed and tested a simple plunger pump, which was operated through a bullock gear, a pair of bullocks walking round on a level path. Owing to the design of the plunger pump, the draft on the neck of the bullocks varied considerably. At the Indian Agricultural Research Institute two different types of bullock-operated pumps were tested during 1954. One of them is a gear pump, which gave a low mechanical efficiency of 11 per cent and an output of 2,600

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[1] These figures are to be found on page 43.

gallons per hour at a depth of 12 ft. This requires considerable improvement. However a gear pump is not best suited for lifting water and its initial cost and maintenance are high. The other pump tested at the Indian Agricultural Research Institute was a 4-cylinder plunger pump, where the cylinders are set on a circle and a common crank shaft operates the pistons. The draft on the bullocks is well balanced. The maximum mechanical efficiency of this pump was 60 per cent and its output was 1,800 gallons per hour (theoretically its output should have been 2,600 gallons per hour). This 4-cylinder plunger pump is being improved by a private firm, so that its output may be increased to double its present capacity. An attempt has also been made to run a diaphragm pump by bullock power. This appears to be the cheapest as regards its capital cost and maintenance, but its technical possibilities for operation by bullocks as well as a windmill require further exploration.

The available models of bullock-operated pumps have not gone into commercial production, as they are still in the process of development. If these are developed it will still be a problem to adapt them to either bullock power or wind power.

QUELQUES PROBLÈMES POSÉS PAR L'UTILISATION DE L'ÉNERGIE ÉOLIENNE EN INDE

par

R. V. Ramiah

RÉSUMÉ

Cette communication rend compte de différentes expériences de rendement effectuées sur des éoliennes d'irrigation dans les Provinces unies et dans les régions de Madras, Mysore et Poona. Il en ressort que les vents de vitesse favorable ne coïncident pas avec les périodes de sécheresse où l'irrigation s'impose. L'auteur mentionne des recherches récemment effectuées par le Département indien de météorologie, et énumère une série de sites favorables à l'installation d'éoliennes.

Il analyse ensuite l'utilisation des éoliennes pour l'élévation de l'eau et esquisse un certain nombre de principes qui doivent présider aux choix des sites de nouvelles expériences, notamment une méthode permettant d'évaluer la production d'énergie ou la puissance d'élévation d'une éolienne.

Il expose également les résultats d'expériences sur le fonctionnement et le rendement des dispositifs indigènes de puisage, ainsi que de récents perfectionnements des norias actionnées par des buffles ; enfin il propose de modifier la conception des pylônes d'éoliennes pour en abaisser le prix et de mettre au point une pompe susceptible de fonctionner en complément d'une noria.

ALGUNOS PROBLEMAS QUE PLANTEA LA UTILIZACIÓN DE LA ENERGÍA HIDRÁULICA EN LA INDIA

por

R. V. Ramiah

RESUMEN

En este documento se exponen los resultados de los experimentos realizados sobre el empleo de aeromotores para el suministro de agua de riego en las Provincias Unidas, Madrás, Mysore y Poona. Esos estudios han demostrado que las velocidades más favorables del viento no corresponden a los períodos en que más se necesita el agua de riego para complementar las precipitaciones pluviales. El autor hace referencia a recientes investigaciones del Departamento Meteorológico Indio e indica los lugares apropiados para la instalación de aeromotores.

Analiza a continuación el problema del empleo de aeromotores para la elevación de agua y establece principios para seleccionar lugares en los que se puedan realizar en el porvenir experimentos con aeromotores. Indica un método para calcular la producción de energía o la cantidad de agua que puede extraerse.

Señala los resultados de los experimentos acerca del funcionamiento y de la eficacia de los aparatos indígenas utilizados para la elevación de agua en la India y de los recientes perfeccionamientos de las bombas accionadas por ganado bovino. Hace sugestiones para dar a la torre del aeromotor una forma que permita reducir su costo, así como para perfeccionar una bomba que funcionara como complemento de la noria en un mismo pozo.

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DISCUSSION

M. Alagoz. A mon avis le problème de l'irrigation comporte des répercussions non négligeables du point de vue social. Il en est de même des machines destinées à utiliser la force du vent. Elles devraient permettre d'améliorer le niveau de vie de la population de l'Inde. Un machinisme de plus en plus développé devrait permettre d'atteindre ce résultat. Bien entendu, il ne faut pas pour autant négliger complètement l'utilisation des animaux de trait.

En un mot, je suis très favorable à l'emploi de plus en plus fréquent de machines productrices d'énergie, en particulier d'énergie électrique, dont l'usage pourrait être grandement accru.

Mr. Golding. Mr. Ramiah has given some very interesting and useful information on the only existing form of power in many of the arid zones of the world, namely, animal power. If the original cost of the animals is taken into account

together with their short working life—and, therefore, high depreciation—and, further, the cost of their fodder is added, it is easy to show that this form of power is, in fact, very expensive. It is not often appreciated that a pair of bullocks drawing water at the rate of 1,000 gallons an hour from a depth of (say) 30 or 40 ft. exert only a small fraction of a h.p. There is no doubt that Mr. Ramiah is right in suggesting the use of wind power to replace, or to supplement, animal power. Even in localities with a low wind speed a suitably designed windmill should be able to produce the small power needed for this purpose. It might well be possible to construct a machine from locally available materials having, perhaps, sails of reed, or bamboo, mats. The larger size of sails needed for low wind speeds need not then involve heavy costs and, though crude, a windmill of this kind could be made and used economically. Again, a low average wind speed is often made up by a few hours when the wind speed is high enough to be usable, followed by a longer period of calm; there may be wind during the day and calm during the late afternoon, night and early morning. This distribution of wind speeds is advantageous because in the daytime there can be several hours of useful output from the wind-driven machine. Detailed records of wind speed at some typical locations should obviously be obtained to enable such possibilities to be determined. The problem in the design of a windmill supplementing bullock power will be to mount it near to the well, in such a way that it does not interfere with the work of the bullocks.

WIND POWER RESEARCH IN ISRAEL

by

J. **Frenkiel**

INTRODUCTION

The importance of developing local energy resources in Israel has been clearly recognized ever since the creation of the state and in 1949, after the Research Council of Israel had been constituted, this body was entrusted with the task of studying the question and making recommendations for research and development. Among the different forms of local energy that came under the Council's consideration, wind energy was bound to attract attention, and in 1950 a wind power committee was formed, originally under the chairmanship of Sydney Goldstein, Professor of Aeronautics at the Haifa Institute of Technology.

The committee proceeded first to examine the existing wind data. These were found to be by no means exhaustive; in fact they were just sufficient to indicate broadly the parts of the country where wind velocities high enough for small-scale electricity generation could be expected. Chief among these were thought to be the hilly regions around Jerusalem and those in the northern part of the country known as Upper Galilee. Around Jerusalem two wind recording stations were operated prior to 1948—on Mount Scopus at the Hebrew University site, and at Ramallah, some 10 miles north of Jerusalem. They both indicated an average wind speed of the order of 10-11 m.p.h. at an effective height of 20 ft., with a principal maximum in winter and a secondary maximum in mid-summer. After 1948, both these stations were left outside the boundary of the state, and of the remaining three pressure tube recording stations (Tel Aviv, Lod and Degania) not a single one could be credited with more than 8 m.p.h. yearly mean.

One additional pressure tube instrument was available and this was installed, on the recommendation of the committee, on Mount Canaan, in Upper Galilee, the highest inhabited spot in Israel (3,100 ft. above sea level).

With no other wind-measuring equipment existing in the country, there was little that the committee could do, and it referred the matter back to the research council with the recommendation that technical assistance be sought to acquire (a) the services of an expert in the field to advise the council on the programme of research, and (b) the equipment necessary to carry out such a programme.

Assistance was obtained in the form of an agreement between Unesco and the Government of Israel, providing for the services of an expert, equipment and training. Following this agreement, E. W. Golding of the Electrical Research Association of the United Kingdom visited Israel at the end of 1951, and recommended the following five stages of research and development: (a) a country-wide wind survey extending for 2-3 years; (b) preliminary trial installations with small (up to 3 kw.) generators to be followed by fuller performance tests; (c) installation and testing of medium-size generators at appropriate agricultural settlements; (d) investigations of the detailed wind structure at one or two sites selected on the basis of (a) as suitable for the establishment of large windmills, connected to the main electricity network; (e) establishment of a large pilot plant.

In the spring of 1952 the author travelled to England, Denmark and other countries to learn at first hand the methods of research on the utilization of wind power in these countries. Upon his return to Israel, the programme based on E. W. Golding's recommendations was begun with stages (a) and (b).

THE GENERAL ENERGY PROBLEM IN ISRAEL

Israel, with its area of 8,000 sq. miles, has at least four distinct climatic zones: (a) the Mediterranean coastal plain; (b) the Jordan valley; (c) the hilly country between the two, reaching the sea at Haifa; (d) the Negev.

Whereas most of the country's 1,700,000 population live in the coastal plain, the density of the rural population is also fairly high in the Jordan valley. The hilly districts where soils have been washed away by erosion over centuries are as yet rather sparsely populated, and the colonization of the arid Negev, which accounts for half of the country, is still in the initial stage.

An interesting feature of the rural population is that something like 25 per cent of it is organized in communal settlements of 50 to 2,000 members; another 25 per cent live in co-operative settlements which are highly organized communities with a fairly high standard of living.

Let us consider now how the energy needs of the Israeli population are satisfied. The centre and north of the country as far as Rosh Pinah are covered with a main electricity supply network fed by oil-fired steam power stations with an overall capacity of 230 mw. The isolated settlements, both in the extreme north and in the south of the country, have local diesel units varying from an individual capacity of 10 kw. to power stations of up to 200 kw. capacity. In addition, a number of industrial plants have oil-fired power stations of their own.

Thus the whole economy of Israel is dependent on imported oil, and every effort should be made to decrease this dependency which weighs heavily on the balance of payments.

Wind power might contribute to a solution of the problem, with a consideration of possible uses as follows: (a) Large scale generation from plants located on favourable sites in the north and centre of the country, connected with the general supply network. (b) Medium sized units working either alone or in conjunction with existing diesel sets in communal settlements. In the first case they could be used for water pumping, distillation, refrigeration, water heating or any other purpose requiring no specific timing. (c) Small wind-driven generators, with a storage battery, for either isolated small communities or individual farmers unable to afford the cost of connexion to high tension lines.

These uses are clearly conditional upon finding adequate wind velocities in the different parts of the country.

WIND SURVEY

Beginning in the spring of 1953, wind measuring sites have been set up all over the country, first in the Negev, then in the Jerusalem hills and finally in the hilly regions of the north. These are usually equipped with cup counter anemometers mounted on 10 ft. poles, but in some cases cup contact anemometers with recording instruments are installed. In choosing sites, account was taken of the wide experience of the British in this field, although it was not always possible to apply their methods exactly under the conditions obtaining in Israel.

The instruments were installed on the peaks of hills in order to make use of the accelerating influence of their slopes on wind velocity. The optimal shape of the hill has not yet been determined. It appears, according to Golding and Stodhart[1] that one should look for hills as steep as possible, provided that their slopes are smooth, without rocks or other protuberances, and that the slope should not change abruptly near the peak, which seems to cause increased turbulence and the lessening of wind velocity in its neighbourhood. For the same reason the placing of measuring instruments on the roofs of buildings is, in general, to be avoided.

On the other hand, it has been found that solid water reservoirs with dome-shaped roofs found on some hilltops in Israel do accelerate the wind flow.

Altogether 16 sites were set up in 1953 and the summary of wind velocities at these sites and at the Tel Aviv and Mount Canaan recording stations, are given in Table 1 (in m./sec.) with corresponding figures for 1954 given in Table 2.

The results of the first year of the wind survey may be summarized as follows:

1. There seems to be no doubt that the Naphtali Mountain Ridge (Misgav Am, Manara and Metzudath Koah) is the windiest region in Israel, the yearly mean at Misgav Am at 3 m. above the water reservoir being 16.4 m.p.h. (7.3 m./sec.), with Manara (9 m.) less by 6 per cent and Metzudath Koah less by about 15 per cent. Moreover, it is a region of steady wind velocities, at least during the summer season in the afternoon hours as the spot measurements made daily at Misgav Am since April this year have shown (Table 3). With the installation of a recorder there, a full picture of hourly velocities is being obtained.
2. Again, the Naphtali Ridge seems to have a wind régime distinct from that of other parts of Upper Galilee, this being easily seen by comparison of monthly wind velocities at Mount Canaan or Sasa with those at Misgav Am (Tables 1 and 2). Whereas on Mount Canaan there is a clear winter peak with a ratio of almost 3 : 1 between the windiest month and the least windy one, there is no such variation along the Naphtali Ridge, where the wind velocity remains comparatively steady all the year round; it is slightly less in the autumn and in the spring, with a monthly mean never differing from the yearly mean by more than

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[1] E. W. Golding and A. H. Stodhart. *The Selection and Characteristics of Wind Power Sites.* Tech. Rep. C/T108, Thorncroft Manor, 1952.

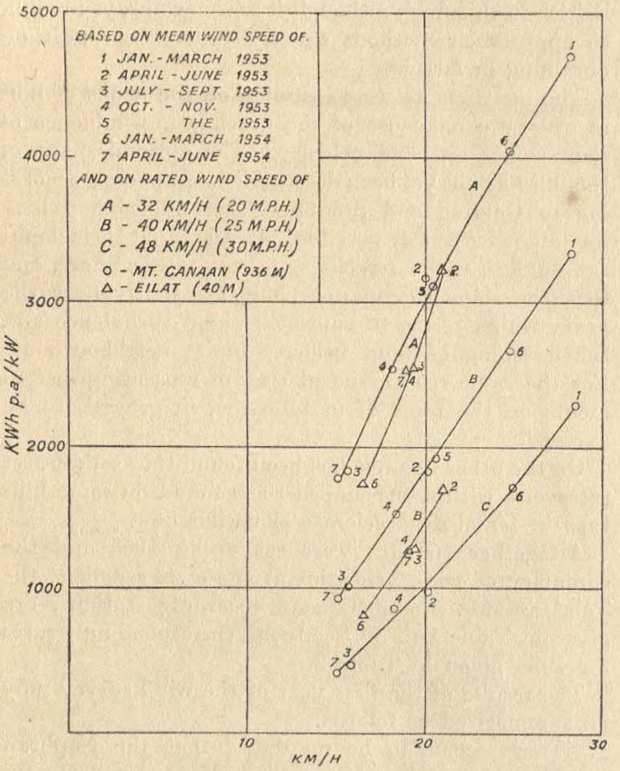

Fig. 1. Wind power research in Israel: specific output *v.* mean wind speed at two sites.

20 per cent. Here is clearly a case of diversity on a seasonal scale over a distance of 30 km. or less. Whether such a diversity exists on a daily and hourly scale as well remains to be seen.

3. Apart from Naphtali Mountain Ridge, other sites in Upper Galilee (in particular Sasa) show fairly high wind velocities.
4. Special mention should also be given to an isolated peak in a broad valley—Givat Hamoreh in the Plain of Esdraelon—which is by far the best site in its range of elevation (up to 500 m.). All the sites mentioned above show definite promise for large-scale generation and it is a happy coincidence that they are to be found in regions which are relatively near to the main supply network.
5. In the arid south (Eilat and Camp Rimon) definitely lower velocities prevail even at the best sites, but they may be assumed to provide an economic basis for a medium-sized windmill. At some very distant and isolated places (Ein Geddi on the Dead Sea shore) small scale wind generators may be worthwhile. Thus in this region too, the wind conditions seem to favour development in line with the needs of the local population.
6. As against this, the seemingly good sites in the central part of the country (Lahav, Ramat Rahel, Mount Carmel) have wind velocities which are too low to make the operation of large units there a worthwhile proposition.

The hourly wind data of 1953 and the first half of 1954 at Mount Canaan and Eilat have been used to construct velocity duration and power duration curves at quarterly intervals. From these, specific outputs were calculated on the assumption of different "boundaries of operation", defined as rated wind velocity (upper boundary) and "cut-in" velocity (lower boundary). These are now shown in relation to the mean velocity of each quarterly period (Fig. 1).

Some points may be mentioned: (a) The points for a particular site all lie on one curve; this shows that the relative weight of different velocities over a certain period, when expressed as a fraction of the mean velocity during that period, remains practically the same, even for as short a period as three months. (b) The difference between the curves for Mount Canaan and Eilat becomes more marked as one passes from lower to higher rated wind speeds. (c) The form of the curves for Mt. Canaan suggests a relationship

$$P_{sp} = K\bar{v}^{n}$$

where $n < 1$ for $Vr < 2v$; $n = 1$ for $Vr = 2v$; $n > 1$ for $Vr > 2v$; v = mean annual velocity; P_{sp} = specific power; Vr = rated velocity.

(d) The curve for Mount Canaan approximates to the curve found by Golding as representative for sites along the western coasts of the British Isles, while that for Eilat differs from it especially as regards the rated wind speed of 40 km.h.

OPERATIONS OF SMALL WIND GENERATORS

In the middle of June 1953 a Jacobs unit of 3 kw. nominal power was put into operation at Eilat, some 30 m. from the Dines wind recording instrument and at the same height as it. The installation has been equipped with a battery of 150 ampere-hours capacity and with a number of electrical indicating and integrating measuring instruments. The installation provides 110 volts D.C. to two government buildings and the connected load is about 3 kw.

The consumption in the period September 1953-September 1954 was 21,834 ampere-hours, corresponding to 1,220 hours of full gross output (18 amps.). The record month was June 1954 with 2,990 ampere-hours, corresponding to 348 kwh. The gross output during the same period was 465 kwh., the difference of 117 kwh. being lost in the field of the generator and battery. Over a 3 months' period (June-August 1954) the average loss in the field and the battery amounted to 26 per cent.

To consider the overall efficiency of the unit, it is evident that it is hardly practicable to obtain a reliable output wind velocity relationship from instantaneous wind values. Instead it seems preferable to relate the amount of energy produced in a certain period to the wind record of that period. If the mean wind speed is taken as the sole criterion of the wind régime, then a three months' period, as was shown before, should be sufficient to evaluate the efficiency of the unit.

If on the other hand, one has a continuous record of mean hourly speeds, a much shorter period should prove sufficient. As an experiment a velocity duration and power-duration curve has been drawn for a 21-hour period between two successive readings of the kwh. meter, as follows:

Date	*Hour*	*kwh. meter reading*
11-9-54	11.20	1815.15
12-9-54	8.15	1835.93
Energy produced		20.78

The energy estimated from the power duration curve is 18.9 kwh.

The agreement seems good if one takes into consideration the inevitable errors of the Dines chart evaluation, and velocity duration curve smoothing; of course, to have any validity, many such checks should be made, reducing successively the time interval between two energy readings.

The overall efficiency of the unit, including the battery, for this 21-hour period would then be "useful electrical energy" divided by "energy available in the wind". The useful energy in that case was 13.5e kwh. (the remainder being dissipated in the field current and the battery), or 0.945 kwh. per m.^{2} (with 14 ft. propeller diameter). The energy in the wind (from the power-duration curve) was found to be 3 kwh., which gives an overall efficiency of 31.5 per cent. Here again many such calculations should be done to arrive at statistically significant figures.

A small Lucas "Freelite" wind unit has been set up recently at Metzudath Koah in the lower part of the Naphtali Mountain Ridge, to charge a 12 volt battery of a receiver-transmitter, but it is as yet too early to draw any conclusions as to its performance.

TABLE 1. Wind speed at wind survey sites (in m./sec.), 1953.

Wind measuring site	*Eilat*	*Camp Ramon*	*Sde Boker*	*Lahav*	*Ein Geddi*	*Ramat Rahel*	*Shoresh*	*Tel Aviv*	*Givat Hamore*	*Kfar Lam*	*Mount Carmel*	*Lavee*	*Mount Canaan*	*Sasa*	*Shamir*	*Manara*	*Misgav Am*
Altitude above sea level (metres)	25	880	460	490	300	820	700	20	510	40	525	300	930	880	220	880	840
Height of instrument above ground (metres)	12	3	3	3	3	3	3	12	3	3	3	9	6	3[2]	3[1]	3[1]	3[2]
Type of instrument	A	B	B	B	B	B	B	A	B	B	B	C	A	B	B	B	B
January								3.4					6.4				
February								5.2					7.9				
March								6.8					9.6				
April	6.0							3.0					5.9				
May	5.6	(4.7)	(3.1)					2.7					5.2				
June	6.1	5.4	3.5			4.8	(3.1)	2.2					5.8				
July	5.1	5.1	3.4			4.1	3.4	2.3	(7.1)		(4.5)		5.6	(7.2)	(3.5)	6.5	7.7
August	5.0		3.3			4.2	3.0	2.8	6.6	(4.1)	4.2		3.8	6.4	3.5	6.3	8.5
September	6.1		3.1			3.6	4.4	2.8	6.1	3.9	3.6		3.8	5.7	2.9	5.9	8.3
October	6.0		3.2			2.9	2.8	2.6	5.3	4.0	3.6		3.5	4.7	3.4	5.0	6.0
November	(4.9)		3.1	(6.2)	(4.4)	3.8		4.1	5.1	4.4	4.0	(3.5)	4.9	5.1	3.3	4.4	5.8
December	5.2		2.2	4.5	2.5	3.1		3.3	5.8	5.8	4.5	3.7	7.1	5.8		4.3	5.7
Yearly								3.4					5.8				

1. Above roof top of a building.
2. Above roof top of a solid water reservoir.

Note : A = Dines pressure tube anemograph. B = cup counter anemometer. C = cup contact anemometer w/recorder.
Figures in parentheses refer to incomplete data.

CONCLUSIONS

In 1953 a country-wide survey was begun, and the first results are very encouraging. It was found that at least in one region (Naphtali Mountain Ridge) there are sites which will ensure a specific output of 4,400 kwh. p.a. for each kw. installed with a 20 m.p.h. rated wind speed, or 3,000 kwh. p.a. for each kw. installed with a 25 m.p.h. rated wind speed.

Several other sites have also been located in the north of the country, for which the corresponding figures would be 3,500 kwh. and 2,200 kwh. These give a basis for commercial operations of large units when these become available.

TABLE 2. Wind speed at wind survey sites (in m./sec.), 1954.

Wind measuring site	*Eilat Dines*	*Camp Ramon*	*Sde Boker*	*Lahav*	*Ein Geddi*	*Ramat Rahel*	*Bnei Brak*	*Tel Aviv*	*Givat Hamore*	*Kfar Lam*	*Mount Carmel*	*Lavee*	*Mount Canaan*	*Sasa*	*Metzudath Koah*	*Manara*	*Misgav Am*
January	4.4		2.5	4.8	3.1	4.7		5.5	6.7	6.6	6.1	4.4	9.1	7.9		4.4	7.6
February	4.2		2.8	4.8	2.8	5.6	4.7	4.9	6.9	6.0	5.4	4.4	6.8	7.8		5.5	8.3
March	5.1		2.6	4.4	3.3	3.4	3.7	3.5	5.9	5.4	4.7	4.2	4.8	6.7		4.8	7.3
April	5.0			4.8	3.7	4.7	4.3		6.1	4.9	4.5	4.4	5.1	6.6		5.5	7.5
May	5.8	4.97		4.2	3.5	3.1	3.6		5.2	3.5	3.4	3.9	3.6	4.9	(5.92)	4.9	6.3
June	5.1			3.9	3.4	(3.8)	3.3		6.8	3.6	3.5	5.7	4.3	6.1	7.0	7.0	8.5
July				3.8	3.3		3.3		6.5	3.5	3.6	5.8		6.1	6.9	6.9	8.4
August		4.97			3.2		3.2		6.2	3.5	4.0	5.3		5.7	6.8		8.0
September							3.6			4.1		4.5			6.4		7.3

TABLE 3. The range of 1200 GMT (1400 local time) spot velocities at Misgav Am (the three minimum and the three maximum velocities in each month are given in m./sec.)

							Mean at 1200 GMT	*Monthly mean*
May 1954	4.2	5.0	5.0	12.8	12.8	14.7	9.4	6.3
June 1954	8.1	8.1	9.4	13.9	13.9	15.0	11.7	8.5
July 1954	8.3	8.3	8.9	14.0	15.0	15.0	11.6	8.4
Aug. 1954	8.3	8.6	8.6	15.0	15.3	15.6	11.6	8.1
Sept. 1954	6.9	7.8	7.8	14.4	16.2	16.7	10.9	7.3

LES RECHERCHES SUR L'ÉNERGIE ÉOLIENNE EN ISRAËL

par

J. Frenkiel

RÉSUMÉ

En 1950, le Conseil de la recherche d'Israël a constitué un Comité de l'énergie éolienne chargé d'étudier la possibilité d'utiliser cette forme d'énergie et de formuler des recommandations sur les recherches et les perfectionnements à entreprendre. Après avoir examiné les données anémométriques existantes et constaté leur insuffisance, le comité a recommandé que le concours d'un expert-conseil, doté de l'équipement voulu, soit sollicité dans le cadre du programme élargi d'assistance technique. Un accord a été conclu à cet effet avec l'Unesco qui a envoyé en Israël, à la fin de 1951, un expert britannique, M. E.W. Golding. Ce dernier a recommandé l'adoption des mesures suivantes :

1. Étude anémométrique sur l'ensemble du pays, d'une durée de deux ou trois ans ;
2. Installation de petites génératrices expérimentales, suivie d'essais à pleine puissance ;
3. Installation et essai de génératrices de moyenne puissance dans des colonies agricoles spécialement choisies ;
4. Étude détaillée du régime des vents dans un ou deux sites propices à l'installation de grandes éoliennes reliées au réseau principal de distribution électrique ;
5. Installation d'une grande centrale pilote.

Les deux premières parties de ce programme ont été mises en train.

Compte tenu des besoins énergétiques du pays, on estime que l'on pourrait utilement avoir recours à l'énergie éolienne pour alimenter : *a*) de grandes centrales situées en des points favorables au nord et au centre du territoire ; *b*) des stations de puissance moyenne fonctionnant dans des colonies agricoles, isolément ou couplées avec les groupes diesel en service ; et *c*) de petites génératrices munies de batteries d'accumulateurs, dans des collectivités ou exploitations individuelles isolées.

La vitesse des vents est bien entendu à considérer, et depuis le printemps 1953 des anémomètres ont donc été installés sur toute l'étendue du territoire. Les résultats de la première année d'études montrent que la chaîne de Nephtali est la partie la plus venteuse du pays ; que dans d'autres régions de la Haute Galilée les vents atteignent des vitesses assez élevées ; qu'un pic isolé, le Givat Hamoreh, dans la plaine d'Esdraelon, offre l'emplacement le plus favorable à l'altitude égale (500 mètres) ; enfin que dans la partie méridionale et aride du pays les vents dominants ont une vitesse plus faible mais suffisante cependant pour faire fonctionner des éoliennes de puissance moyenne dans de bonnes conditions de rentabilité.

Les débits spécifiques ont été calculés pour Eilat et pour le mont Chanaan. Ils sont indiqués sur la figure 1 où ils sont rapportés à la vitesse moyenne du vent pour chaque trimestre.

En juin 1953, un groupe Jacobs d'une puissance nominale de 3 kW a été installé à Eilat ; l'auteur analyse les données tirées de son fonctionnement.

INVESTIGACIONES SOBRE LA ENERGÍA EÓLICA EN ISRAEL

por

J. Frenkiel

RESUMEN

En 1950, el Consejo de Investigaciones de Israel creó un Comité sobre Energía Eólica para estudiar las posibilidades de utilización de dicha energía eólica y formular recomendaciones para realizar investigaciones sobre la misma y dar aplicación práctica a sus resultados. El examen realizado por el Comité de los datos existentes sobre el viento, sólo sirvió para demostrar su insuficiencia, recomendándose que se consiguieran por conducto del Programa Ampliado de Asistencia Técnica los servicios de un asesor experto con el equipo necesario. Se concertó un acuerdo con la Unesco, que a fines de 1951 envió a Israel a E.W. Golding (Reino Unido). Dicho experto recomendó:

1. La realización de estudios eólicos sobre todo el territorio del país durante un período de dos o tres años;
2. La instalación preliminar, con carácter experimental, de pequeños generadores, seguida de experimentos de progresiva importancia;
3. La instalación y prueba de generadores de tamaño mediano en ciertas colonias agrícolas;
4. La investigación detallada de la estructura eólica en uno o dos lugares elegidos para la instalación de grandes aeromotores conectados a la red eléctrica principal;
5. La instalación de una gran planta generadora experimental.

El programa ha empezado a realizarse por sus partes 1 y 2.

En vista de las necesidades energéticas del país se considera que la energía eólica puede emplearse provechosamente para: *a*) producción de energía eléctrica en gran escala en determinados lugares del norte y centro del país; *b*) centrales de tamaño mediano que trabajen independiente o conjuntamente con los grupos electrógenos accionados a base de los motores diesel de que disponen las colonias agrícolas; *c*) pequeños grupos provistos de acumuladores para las comunidades aisladas o las granjas particulares.

Esos usos están condicionados a la existencia de adecuadas velocidades del viento. A partir de la primavera de 1953 se instalaron anemómetros en todo el país. Los resultados del primer año de trabajo en lo que al estudio del viento se refiere indican: que la sierra de Neftalí es la región más ventosa del país; que en otros lugares de la alta Galilea soplan vientos de una velocidad bastante elevada; que un pico aislado, el Givat Hamoreh en la llanura de Esdrelón, es el mejor lugar por su elevación (500 metros); que en las zonas áridas de la región meridional las velocidades del viento son inferiores, aunque constituyen una base económica para la instalación de aeromotores de tamaño mediano.

Se calculó la producción específica en el monte Canaán y Eilat. Esos datos figuran en la figura 1 en relación con la velocidad media de cada trimestre.

En junio de 1953 se instaló en Eilat un grupo Jacobs de 3 kW de potencia teórica; el autor analiza los datos obtenidos desde su entrada en funcionamiento.

DISCUSSION

Mr. Golding. Mr. Frenkiel is to be congratulated on the interesting work which he has done and is doing in Israel. I have had the privilege of being connected with the Israel investigations from their outset and am very glad to notice, from the results given in the paper, that some of the survey sites are showing really useful wind speeds. There are possibilities in that country for the use of wind power on all three scales, small, medium and large, because the geographical and climatic nature varies so greatly from its southern-most tip at Eilat on the Red Sea—a truly arid region—to the much more temperate area in Upper Galilee where well-exposed hills give promise of an economic output from wind-driven generators which might be built on them. Again, the agricultural settlements which are located in the northern Negev, and other districts remote from electricity networks, could use power from wind-driven machines in order to reduce the consumption of diesel fuel for which transport costs tend to be high. I was especially interested in the comparison which Mr. Frenkiel gives, in his graph relating to specific output and mean wind speed, between his results and those which we have obtained in Great Britain. The close agreement which he finds, except at Eilat, is very encouraging and shows the value of the exchange of information between workers in the same field of research in different countries.

POSSIBILITY OF WIND POWER UTILIZATION IN SAURASHTRA

by

U. J. BHATT

LOCATION AND AREA

Saurashtra is the most westerly of the states of India, and occupies an area of 22,000 sq. miles. It is a large peninsula, having water on three sides: to the north the Gulf of Kutch, to the southwest the Arabian Sea and to the east the Gulf of Cambay. It is this special configuration which gives rise to winds of perceptibly high velocity almost throughout the year.

TOPOGRAPHY

The main ridges in Saurashtra start from Girnar, in Junagadh, which is about 3,600 ft. high, and continue to the southwest and north. An independent ridge, Barada, runs west to east in the region of Porbandar. The central part of the state has an elevation of 500-1,200 ft. above sea level. This forms the watershed of the peninsula.

Additionally there are ridges parallel to the valleys, radiating from the centre. These ridges have elevations of from 300-1,000 ft. above sea level.

METEOROLOGICAL OBSERVATIONS

The following table shows the maximum and minimum monthly wind velocities at stations on the coast (1-6) and in the interior (7 and 8).

Station	*Maximum wind velocity*		*Minimum wind velocity*	
	month	*m.p.h.*	*month*	*m.p.h.*
1 Jamnagar	June	15.2	November	4.0
2 Dwarka	August	16.3	December	5.4
3 Porbandar	July	15.6	December	4.0
4 Veraval	August	22.0	December	6.6
5 Mahuva	August	9.8	February	2.2
6 Bhavnagar	June	14.4	December	4.7
7 Surendranagar	—	—	December	2.7
8 Rajkot	June	18.1	February	2.7

The table shows that the wind velocities at these stations are attractive from the point of view of wind energy utilization.

All who have travelled through Saurashtra, no matter what the season, have noticed the high wind velocities. Small windmills for pumping water have been operating in Saurashtra during the past sixty years. Some were installed by the railway companies, and half a dozen are still working at railway stations. Water for agricultural purposes is pumped by wind power at about 60 places near Bantva. If a really suitable unit were available for lifting water, lighting and air-conditioning there should be a good demand for it.

WIND POWER FOR GENERATING ELECTRICITY

Another possibility would be to establish a co-ordinated system of electrical generating stations operated by wind power, and feed the power into the present grid system. The electric grid project of the Saurashtra Government depends entirely on thermal generation. Though the state has a progressive policy of harnessing its water resources for irrigation in the semi-arid area, the streams are seasonal and there is little possibility of using them for power generation.

The location of Saurashtra makes fuel for generation of electricity expensive, the cost varies from 1.125 to 1.6 annas and rises as high as 2 annas in certain localities. This increases the attractiveness of studying the feasibility of generating electricity by wind power for feeding into the grid.

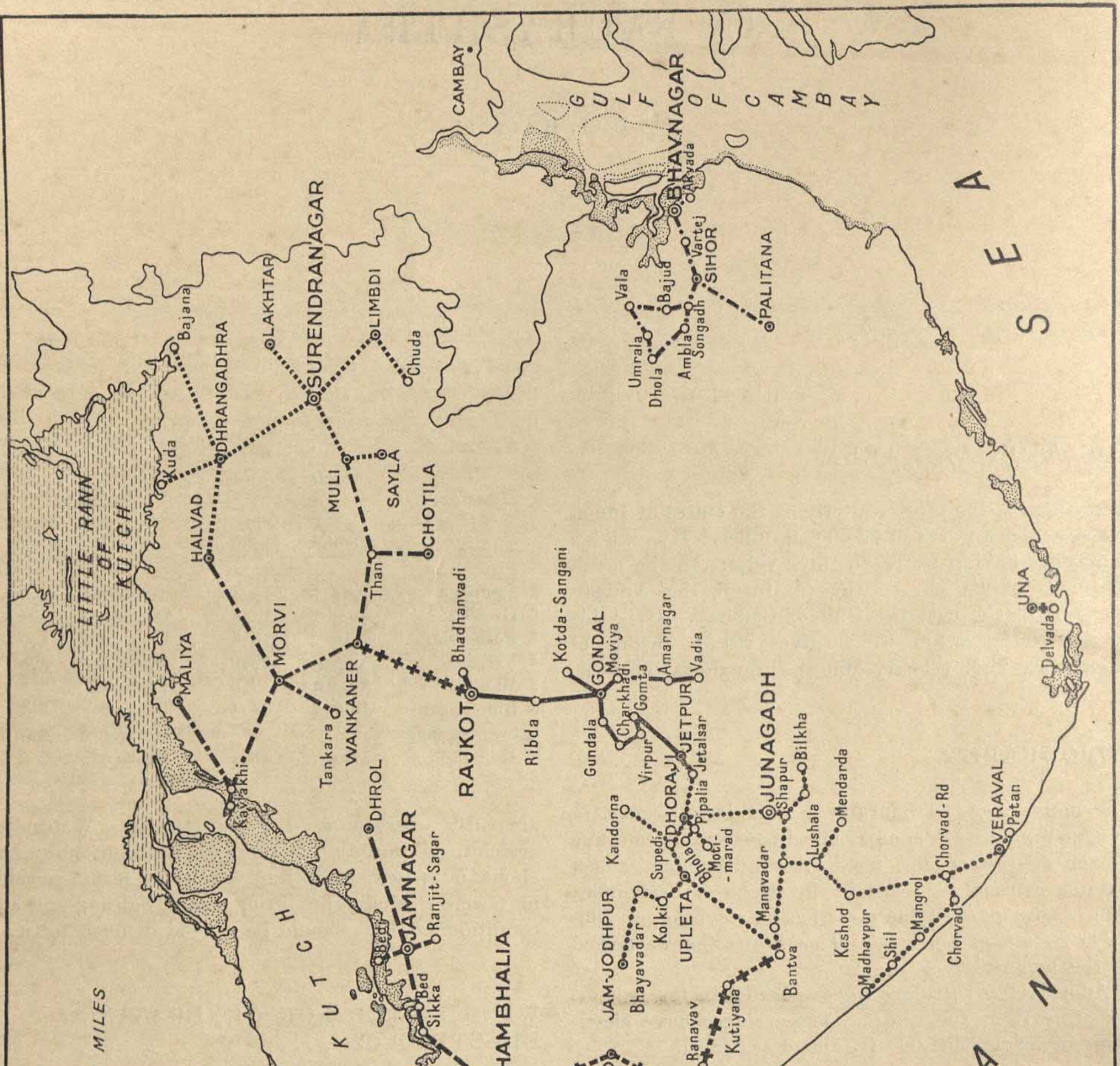

Fig. 1. Map of Saurashtra showing transmission and distribution lines and area of supply of each major station.

POSSIBILITÉS D'UTILISATION DE L'ÉNERGIE ÉOLIENNE DANS L'ÉTAT DE SAURASHTRA

par

U. J. Bhatt

RÉSUMÉ

L'État de Saurashtra est situé à l'extrémité occidentale du territoire indien ; il occupe la vaste péninsule de Kathiawar (57.000 km^2), que bordent au nord le golfe de Katch, au sud-ouest la mer d'Oman et à l'est le golfe de Cambaye. C'est à cette configuration qu'il doit d'être soumis pendant presque toute l'année à des vents d'une vitesse très élevée.

Les principales chaînes montagneuses du Saurashtra s'étendent vers le sud-ouest et le nord à partir du pic de Girnar, dans le Junagadh (1.100 mètres environ). Une chaîne isolée, celle de Barada, traverse d'ouest en est la région de Porbandar. La ligne de partage des eaux de la péninsule se trouve dans la partie centrale de l'État, à une altitude de 150 à 370 mètres.

Enfin des crêtes de 90 à 300 mètres d'altitude bordent les vallées situées en éventail à partir du centre.

Le tableau figurant à la page 115 donne les mois de plus haute et de plus basse vitesses du vent dans des régions de la côte (1 à 6) et de l'intérieur (7 et 8).

Ces chiffres semblent fort encourageants du point de vue de l'exploitation de l'énergie éolienne.

Tous ceux qui ont voyagé dans l'État de Saurashtra, en quelque saison que ce soit, ont remarqué combien les vents y sont violents. De petites éoliennes servant au pompage de l'eau sont en service dans cette région depuis une soixantaine d'années. Certaines ont été installées par les compagnies de chemin de fer et on en trouve encore une demi-douzaine dans des gares. Près de Bantva, une soixantaine de localités irriguent leurs terres au moyen de l'énergie éolienne. Il est probable que si l'on trouvait un type réellement pratique d'aéromoteur pouvant servir au puisage de l'eau, à l'éclairage et au conditionnement de l'air, les débouchés seraient considérables.

Une autre solution consisterait à établir un ensemble coordonné de centrales éoliennes qui alimenteraient le réseau actuel de distribution d'électricité. Ce dernier est à l'heure actuelle alimenté exclusivement par des centrales thermiques. Le gouvernement a des projets d'aménagement hydraulique en vue de l'irrigation de la région semi-aride, mais les cours d'eau sont saisonniers et il ne serait guère possible d'en tirer parti pour produire de l'électricité.

En raison de la situation géographique de l'État, le combustible nécessaire aux centrales thermiques est très coûteux. (Le prix de revient atteint 1,125 et 1,6 annas, et même jusqu'à 2 annas dans certaines localités.) C'est là une raison de plus pour étudier la possibilité d'alimenter le réseau de distribution avec du courant provenant de génératrices éoliennes.

POSIBILIDAD DE UTILIZAR LA ENERGÍA EÓLICA EN SAURASHTRA

por

U. J. BHATT

RESUMEN

Saurashtra es el más occidental de los Estados de la India, y tiene una superficie de 57.000 km². Es una gran península rodeada de agua por tres partes: limita al norte con el golfo de Kulch, al sudoeste con el mar Arábigo y al este con el golfo de Cambay. Esa configuración especial es la que da origen a vientos de gran velocidad durante casi todo el año.

Las sierras principales de Saurashtra empiezan en Grinar (Junagadh) donde tienen unos 1.100 m. de altura, y continúan hacia el sudoeste y el norte. Una sierra independiente, la de Barada, atraviesa de oeste a este la región de Porbandar. La parte central del Estado está situada entre 150 y 370 metros sobre el nivel del mar.

Además, hay sierras paralelas a los valles, que irradian desde el centro. Esas sierras tienen elevaciones de 90 a 300 metros sobre el nivel del mar.

El cuadro reproducido en la página 115 muestra las velocidades mensuales máximas y mínimas del viento en estaciones costeras (1-6) y en el interior (7 y 8).

El cuadro muestra que la velocidad del viento en esas estaciones es valiosa desde el punto de vista de la utilización de la energía eólica.

Todas las personas que han viajado por Saurashtra, sea cual fuere la estación, se han podido dar cuenta de la elevada velocidad del viento. En los últimos sesenta años han funcionado en Saurashtra molinos de viento para bombear el agua. Algunos fueron instalados por las compañías ferroviarias, y media docena de ellos siguen funcionando en las estaciones de ferrocarril. El agua para fines agrícolas se bombea con la ayuda del viento en unos sesenta lugares cerca de Bentva. Un grupo que cumpliese bien las funciones de elevar el agua, producir electricidad y permitir el acondicionamiento de aire encontraría evidentemente gran demanda.

Otra posibilidad consistiría en establecer un sistema coordinado de centrales eólicas y conectarlo a la red eléctrica existente. En la actualidad, el sistema de suministro de energía utiliza exclusivamente centrales térmicas. Aunque el gobierno de Saurashtra sigue una política progresiva de aprovechamiento de los recursos hidráulicos para el riego de la zona semiárida, las corrientes de agua están sometidas a un régimen de estiaje y hay pocas posibilidades de utilizarlas para la producción de energía eléctrica.

La situación geográfica de Saurashtra hace que el combustible para la producción de electricidad resulte caro, ya que el costo varía entre 1,125 y 1,6 anas y sube hasta 2 anas en algunas localidades. Esto hace que la posibilidad de producir electricidad por medio de la energía eólica para conectarla a la red general sea tema muy interesante.

DISCUSSION

MR. GOLDING. The wind power requirements which Mr. Bhatt has mentioned for Saurashtra are somewhat different from those for other parts of the arid areas of India. In his district there is an electrical network and, as he has told us, there is apparently a good wind régime. There is thus the possibility of using wind-driven machines of an appreciable size, such as several hundred kw. capacity, which can feed their output directly into the network. With the high fuel component of energy cost which he has mentioned, there should be a good possibility of utilizing wind-driven generators economically. Clearly, the first thing to do is to make a comprehensive wind survey using selected sites in the Saurashtra area.

THE UTILIZATION OF WIND, SOLAR RADIATION AND OTHER LOCAL ENERGY RESOURCES FOR THE DEVELOPMENT OF A COMMUNITY IN AN ARID OR SEMI-ARID AREA

by

E. W. Golding and M. S. Thacker

INTRODUCTION

The development of any arid or semi-arid area implies the establishment of communities to live and work there to bring about this development by their efforts in agricultural or other pursuits which exploit the resources of the surrounding district. But man's efforts, unsupported by larger sources of power than his own, are usually insufficient to take him beyond a primitive form of existence unless his land is naturally very productive—a condition which does not apply in the areas being considered. Animal power, from bullocks, horses or camels, is an obvious source, but it has the disadvantage that the animals themselves are consumers of agricultural products on a not inconsiderable scale, e.g. a bullock needs some 12 to 15 tons of fodder per annum. One turns then to the possibilities of mechanical power for which some natural source of energy is needed such as "fuel" (using the term in the broad sense as the basic energy to be converted into usable form).

To bring in such "fuel", either in the liquid form of oil to drive engines, or in more refined form as electrical energy through transmission lines, may appear to be an easy solution but this involves payment both for the "fuel" itself and for its transport. For an area remote from the main sources of supply the latter cost is often prohibitively high ; hence the need to consider the employment of local energy resources to carry the development forward to the stage at which organized importation of "fuel" or electrical energy from a distance is economically justifiable.

The circumstances governing the continued existence of a rural community, and the conditions of life there, obviously vary widely. At the lower end of the scale, there is bare subsistence in a way of life little better than that of animals ; in the middle state the amenities are just sufficient to hold the inhabitants on the land rather than forcing them to seek a better standard of living in urban areas ; at the uppermost level there is a prosperous mode of life which must be the aim of true development. The discussion in this paper is concerned with the steps which could be taken to raise the standard from the middle to the upper level, in the case of established communities, and to ensure that newly settled communities in arid or semi-arid areas are afforded amenities which are, at least, sufficient to make life bearable during the early stages of development.

It must be accepted that no continuously available source of energy exists in the locality concerned and that a combination of sources will be needed to provide an adequate total amount. To assess the possibilities, therefore, we must consider on the one hand the energy requirements of a community and, on the other hand, the energy resources which might be employed, economically, to supply these requirements. Basically, there are ample resources, in the forms of wind and solar radiation alone, to provide all the probable needs of most arid zone communities, but the main problem is to capture the energy without involving excessive costs and to apply it satisfactorily to varying purposes for the community's development.

THE CHARACTERISTICS OF LOCAL ENERGY RESOURCES

These resources can be listed quite briefly as: wind energy, solar radiation and (sometimes) vegetable wastes or other forms of solid fuel. (Occasionally there may be a little water power but this would be unusual and ought not to be counted in a general consideration.)

They have the common characteristic that they are not continuously available but, in fact, their occurrence is not completely random so that their availability can be relied upon with some assurance provided that no very precise timing is expected. Let us consider them separately.

WIND POWER

At any given site the annual average wind speed remains nearly constant from year to year (within ± 10 per cent or even less). Again, windy seasons of the year can be clearly distinguished in most areas and, in these seasons, diurnal variations are often quite regular so that one can, for example, frequently rely on wind during the hours from noon to sunset.

To gain an impression of the annual energy obtained by employing a suitably designed wind power plant at a site in an arid zone let us take the following hypothetical case: an annual mean wind speed of 4.5 m./sec., the machine having an overall efficiency of 30 per cent and producing its full output at a wind speed of 9 m./sec.

The annual energy obtained per square metre of surface swept by the rotor would be approximately 250 kwh.—enough to provide electric lighting for a small house. At such a site there would probably be, during the year: 700-1,000 hours of complete calm, 2,500-3,000 hours of wind speed between zero and 3.5 m./sec., 4,500-5,000 hours of wind speeds between 3.5 and 13 m./sec. and 50-100 hours of wind speed over 13 m./sec.

There would, therefore, be a prospect of the wind-driven machine being in operation, with varying output, for some 4,000 hours (almost 50 per cent of the year) provided it were designed to use low wind speeds.

SOLAR RADIATION

Although the maximum value of direct solar radiation on a surface normal to the rays may reach 1.12 kw./m.^{2}, an average value of only 0.15-0.2 kw./m.^{2} throughout the year is as much as can be relied upon. The energy becoming available is thus some 4 kwh./m.^{2} per day or 1,460 kwh./m.^{2} in the year.

If the efficiency of collection is 50 per cent this means that over 700 kwh. per annum can be collected from each square metre of horizontal surface.

For this energy source there is a greater certainty of occurrence—and non-occurrence, during the night—than for wind power, and the sunny periods of the year are also well marked. The most serious difficulty lies in the fact that the usable energy is in thermal form (instead of mechanical form as with wind power) so that its conversion to mechanical power involves a cost which, in the present stage of development, cannot be determined exactly but which is likely to be rather high.

WOOD AND OTHER VEGETABLE MATTER

In arid and semi-arid areas the general absence of vegetation is closely associated with desert conditions and destruction of such vegetation, when it does exist, is to be discouraged. Nevertheless, small quantities of waste material which could be used as fuel for steam raising or for use in a hot air engine, are sometimes available. In some areas plantations of trees have been made to provide a future supply of fuel and give valuable shade during their growing period. If it were kept under control the use of this material would afford an energy source, with a different characteristic, to supplement those of variable availability ; it represents stored energy for use whenever required.

Small engines which are being developed to use fuel of this kind will probably consume (according to its calorific fuel) some 12 to 15 lb. per h.p.-hour or, say, 20 lb. per kwh.

An annual consumption of 10 tons would thus provide about 1,100 kwh.

THE COMBINED USE OF ENERGY RESOURCES

The costs attached to the production of usable energy from the free sources of wind and sun are fixed for any particular power plant. Apart from a small sum for maintenance, they are simply the annual charges for interest and depreciation, so that the greater their output and the higher the proportion of it which is effectively used, the lower the cost per unit of energy.

There are, in fact, two sides to the question of economy in the combined use of local energy resources. The first is concerned with planning the loads so that the fullest possible use is made of the energy as and when it becomes available. The second must take into account the difficulty of planning for completely random use, without storage, and must aim at dovetailing the power from the different sources so that the supply is continuous. Storage of energy, by devices serving no other purpose, is to be avoided as far as possible because these add to the capital cost of the whole equipment and, involving conversions of energy from one form to another, introduce losses so that the total energy output is reduced. Maximum use should, however, be made of loads having inherent storage and for which no precise time schedule need be followed ; a good example is water pumping which, within wide limits, can be done at any time and which stores energy in potential form.

Not all of the loads to be supplied for a community are in this category ; some, e.g. lighting, call for a power supply at very definite times while others, such as most of the agricultural processes, demand, at least, that the power shall be available during daylight hours. Water heating, refrigeration and loads having some thermal storage, can use energy with some freedom in timing provided that the periods during which supply is lacking are not too long.

Thus, it is clear that the loads have their individual characteristics as well as the energy sources, and for economic utilization the load and energy characteristics must be closely matched. The problem in planning power supplies for communities in arid zones can be regarded as an extension of the load-spreading problem, which has become familiar to electric power engineers during recent years when the generating capacity in power stations has been inadequate for the rapid increases in demand.

Another matter of importance when the combined use of energy resources is being considered is that of the suitability of each particular form of power for the different loads. Theoretically any form of energy could be used for any load but, as already mentioned, conversions from one form to another are wasteful and expensive. It would obviously be uneconomic, for example, to provide electric light from solar radiation via an engine driving a generator when a wind-driven generator could be used instead. On the other hand, water heating and distillation can be done more easily by direct use of solar heat.

In Table 1 a number of possible loads, in a rural community, are placed in classes according to their timing requirements and the means by which they might be supplied are indicated with some notes on the combinations which might be employed.

The loads in the first column can use energy up to the limits set by the community's requirements for domestic water supply and for hot water or steam (for sterilizing). The irrigation load is less likely to be limited since, if both surface and spray irrigation are combined, any surplus energy can be absorbed without difficulty. All the loads in this class either have inherent storage or are capable of accepting random energy for immediate use. Those in the second column are not quite so flexible. They can use limited amounts of energy, fixed by the needs of the community for the products concerned, during the daytime but obviously they do not occur every day in all instances, e.g. threshing is only a seasonal load.

Cooking has more precise requirements for timing. It is not a load which can be supplied from a random source of energy alone; provision must be made for the use of energy sources in combination to ensure that power (in thermal form) is available when required. Fans, air conditioning and refrigeration equipment call for continuity of supply throughout the daytime. Lighting also has a fixed time requirement and battery storage to ensure the supply is essential. The same applies, though in a smaller degree, to the provision of power to operate a radio set or for small domestic purposes.

TABLE 1

Random (Day or night)	*Day (No precise time)*	*Day (Precise times)*	*Night (Precise times)*	*Wind power*	*Solar radiation*	*Vegetable waste*	*Notes*
Domestic water supply				W		V	V only supplementary
Water distillation					S		
Irrigation				W		V	V only supplementary
Water heating				W	S		W only supplementary
Steam raising				W	S		
	Threshing			W		V	V only supplementary
	Grinding			W			
	Food mixing			W			
	Fodder chopping			W			
	Small industrial or agricultural power			W		V	In combination
		Cooking		W	S	V	In combination
		Fans and air conditioning refrigeration		W	S		In combination
			Lighting	W			With battery storage
			Radio and small domestic power	W			With battery storage

The table suggests that wind power should be used mainly for loads needing power in mechanical form, and solar radiation for those calling for heat, while the energy from the combustion of waste material plays a supplementary role acting as a stand-by to ensure continuity of supply when the other two sources are lacking.

Except for the electric battery, no specific provision has been made for energy storage because of its generally high cost. Before ending this section, however, we should perhaps mention some suggestions which have been made for various means of energy storage. Among these are: (a) storage of wind energy in chemical form by the electrolysis of water to provide hydrogen which is then stored and subsequently used as a fuel; (b) storage of wind energy by arranging for the wind rotor to drive a compressor, the compressed air being used later as a power supply; (c) the conversion of waste vegetation into alcohol by fermentation; (d) storage of solar radiation by growing algae (e.g. chlorella) which can be used as an animal foodstuff, as a fuel, or as a base for the production of important pharmaceutical substances.

Doubtless all these suggestions are technical possibilities but they have not been taken into account in the preceding discussion because their economy has not yet been fully established and must depend upon the particular circumstances of their use.

PRACTICAL OPERATION

The use, in combination, of equipment operated by wind, sun and waste material in such a way as to fulfil the needs of a community and, at the same time, to ensure economy by making full use of all the plant installed, would certainly call for careful planning. The details of operation must, of course, be influenced so much by local conditions applying to the life of the community that any attempt to set them out here would be unrealistic. The only satisfactory way by which the practical possibilities can be determined is to run an experimental combination of equipment at a selected community, the inhabitants of which are willing to co-operate in running it. Nevertheless, one can form a fairly clear impression of the general possibilities, and can estimate what plant would be needed, by listing the probable energy consumptions and power needs for an imaginary case. This is attempted below.

Consider a community of some 40 to 50 families located in a sunny district where the wind speed at one or two selected sites is 10 to 12 m.p.h. (about 5 m./sec.) and where a few tons per annum of waste material can be relied upon for fuel. In Table 2 the various loads which were classified in Table 1 are listed, together with some notes on their probable magnitudes and the annual energy consumptions which they would call

TABLE 2

Load	*Basis of estimation*	*Annual energy (kwh.)*	*Power needed (kw.)*	*Notes*
Domestic water supply	40 gals. per family per day	2 500	1	Entirely from wind power with storage reservoir.
Water distillation	A total of 5 gals. per day	6 500	0.75	From solar radiation with collector of 5 m.^{2} giving a 24 hour average power of 0.75 kw.
Irrigation	50-100 acres irrigated with 5 to 10 inches	30 000	12	Entirely from wind power.
Water heating and steam raising	7-10 gals. per family per day	30 000	4 or 6	Solar radiation from collector of 50 m.^{2} giving 4 kw. continuously on 24 hour basis. Occasional 6 kw. wind power.
Threshing	Total of 200 tons per annum	2 500	10	Done by wind power when available.
Grinding, food mixing and fodder chopping	Total of 50-100 tons of each per annum	2 500	8	Wind power.
Miscellaneous small power		5 000	5	Wind power with waste material as supplementary.
Cooking	Equivalent of 1 to 1.5 kwh. per family per day	20 000	20	Solar cookers. Waste material as fuel. Wind power supplementary when available.
Fans, air conditioning and refrigeration		20 000	10	Wind power with solar collectors.
Lighting and small domestic powery		10 000	5	Wind power with electric battery.
TOTAL		129 000		

for. Power requirements, or the size of solar plant needed, are also estimated.

Individual items in the table are doubtless open to question but the estimates of consumption may be acceptable, at least as a basis for discussion, and it is probable that the total annual energy consumption, which corresponds to 2,500 to 3,000 kwh. per family, is reasonable.

As for the plant required, this could be: (a) 25 kw. of wind power plant having an annual output of 2,000 kwh./kw. This would furnish 50,000 kwh. of energy to be distributed as follows: domestic water supply, 2,500; irrigation, 30,000; grinding, etc., 2,500; miscellaneous power, cooking, etc., 5,000; lighting and domestic power 10,000.

(b) Solar plant, comprising: small solar cookers, a collector of 5 m.^{2} for distillation, collectors having a total of 50 m.^{2} for water heating, collectors totalling 50-100 m.^{2} for air conditioning and refrigeration.

(c) Two steam or hot air engines each of 3 h.p. (2.5 kw.), to be used—mainly as stand-by plant—for some 400 hours per annum and to produce about 2,000 kwh. as supplementary heat for cooking, wood or other solid fuel to the equivalent of about 5,000 kwh. per annum would be needed.

There should be no difficulty in making full use of the installed plant. The solar plant, especially the large collectors, will receive and use the available radiation automatically. Distribution of the power output from the wind power plant would need planning with the inclusion of a scheme for automatic switching to pass on the power from one load to another as required. It will be seen that the total of the power loads for which the wind power machines can be used considerably exceeds the 25 kw. which it is suggested should be installed so that, when the wind is strong enough to provide their full output, this can be absorbed effectively.

CONCLUSION

This paper has been prepared because the authors are convinced that economic utilization of local energy resources is possible provided that sufficient attention is paid to the installation itself and to the methods to be followed in its operation. They feel strongly that the establishment of one or two experimental installations at suitable communities in different parts of the world is the best—if not, indeed, the only—way to determine the practicability of such a scheme.

The question of costs of equipment has not been discussed in the paper in view of the uncertainty of the eventual costs for some of the plants now under development. The economy of wind power alone has already been fully dealt with by one of the authors[1] and the problem in planning an economical combined installation must be tackled on the basis of a comparison with the alternative costs of power production in remote areas, using oil as the source of energy.

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[1] See Unesco/NS/AZ/139.

L'UTILISATION DE L'ÉNERGIE ÉOLIENNE, DU RAYONNEMENT SOLAIRE ET DES AUTRES SOURCES LOCALES D'ÉNERGIE POUR LE DÉVELOPPEMENT DES COLLECTIVITÉS DES RÉGIONS ARIDES OU SEMI-ARIDES

par

E. W. GOLDING et M. S. THACKER

RÉSUMÉ

Cette communication étudie les mesures à prendre pour porter les conditions d'existence d'une collectivité rurale dans une région aride ou semi-aride, à partir d'un niveau à peine capable d'éviter l'exode, jusqu'à un stade de prospérité, et pour permettre aux collectivités nouvellement installées en de telles régions de

bénéficier d'avantages capables, tout au moins, de rendre leur existence supportable pendant la phase initiale de la mise en valeur.

Les auteurs prennent le cas de localités où il n'existe aucune source d'énergie utilisable de façon continue, si bien qu'il faut en combiner plusieurs. Pour déterminer les possibilités, il faut considérer aussi bien les besoins en énergie de la collectivité en question que les ressources qui peuvent servir à les satisfaire.

Les ressources énergétiques disponibles sont les suivantes : énergie éolienne, rayonnement solaire et (parfois) résidus végétaux et autres formes de combustible solide. A condition d'être conçue pour utiliser les vents de faible vitesse, une machine aéromotrice pourrait fonctionner pendant près de la moitié de l'année. Si l'appareil employé pour capter l'énergie solaire a un rendement de 50 %, la quantité qu'il sera possible de capter par mètre carré de surface horizontale dépassera 700 kWh par an. Enfin on construit actuellement de petits moteurs qui peuvent produire environ 1.100 kWh contre 10 tonnes de combustibles végétaux.

Les caractéristiques des différentes sources d'énergie et des charges auxquelles elles peuvent faire face sont analysées et présentées dans le tableau 1. Il en ressort que l'énergie éolienne convient surtout à la production d'énergie mécanique et l'énergie solaire à la production de chaleur, tandis que l'énergie fournie par la combustion de déchets végétaux doit être considérée comme un appoint pour les périodes où les deux autres sources font défaut.

L'emploi combiné d'appareils alimentés en énergie par le vent, par le soleil et par la combustion de déchets exigerait certainement l'établissement de plans très étudiés. La seule façon d'évaluer convenablement les possibilités pratiques consisterait à faire fonctionner une combinaison d'appareils dans une collectivité donnée. Néanmoins, on peut s'en faire une première idée en dressant la liste des consommations probables d'énergie et des puissances requises dans un cas imaginaire. C'est ce qui est fait dans le tableau 2 où, pour une collectivité de quarante ou cinquante familles environ, située dans une région ensoleillée où la vitesse du vent est de 16 à 20 kilomètres à l'heure, figurent les différentes charges énumérées dans le tableau 1.

Les auteurs se déclarent convaincus qu'une utilisation économique des ressources locales d'énergie est possible pourvu que l'on apporte tout le soin nécessaire tant aux installations proprement dites qu'aux méthodes d'exploitation.

LA UTILIZACIÓN DE LA ENERGÍA EÓLICA DE LA RADIACIÓN SOLAR Y DE LAS DEMÁS FUENTES LOCALES DE ENERGÍA PARA EL DESARROLLO DE LAS COLECTIVIDADES DE LAS REGIONES ÁRIDAS O SEMIÁRIDAS

por

E. W. GOLDING y M. S. THACKER

RESUMEN

Esta comunicación estudia las medidas que deben adoptarse para mejorar las condiciones de existencia de una colectividad rural en una región árida o semiárida, de modo que pase de un estado en que el nivel de vida basta muy justamente para retener a los habitantes a un estado de prosperidad, y para que las colectividades recientemente instaladas en esas regiones se beneficien de ventajas suficientes cuando menos para hacerles la existencia soportable durante la fase inicial de su desarrollo.

Los autores estudian el caso de localidades donde no existe ninguna fuente de energía que pueda utilizarse

de manera continua y en las que se precisa recurrir simultáneamente a varias de ellas. Para determinar las soluciones posibles, es preciso conocer, por una parte, las necesidades energéticas de la colectividad y, por otra, los recursos que pueden servir para satisfacerlas.

Los recursos energéticos disponibles son los siguientes: energía eólica, radiación solar y (a veces) los residuos vegetales y demás formas de combustible sólido. A condición de ser concebido para utilizar los vientos de poca velocidad, un aeromotor podría funcionar durante casi la mitad del año. Si el aparato empleado para captar la energía solar tiene un rendimiento del 50 %, la cantidad que podrá captarse por metro cuadrado de superficie horizontal sobrepasará los 700 kWh anuales. Por último, actualmente se construyen pequeños motores que pueden producir unos 1.100 kWh con un consumo de 10 toneladas de combustibles vegetales.

Las características de las diversas fuentes de energía y de las "cargas" a que pueden hacer frente son analizadas y presentadas en el cuadro 1. De él se desprende que la energía eólica conviene sobre todo a las "cargas", que exigen el empleo de energía mecánica y la energía solar a la producción de calor, mientras que la energía suministrada por la combustión de desperdicios vegetales debe considerarse como una ayuda para los períodos en que no producen las otras dos fuentes.

El empleo combinado de aparatos alimentados por la energía eólica, por la solar y por la combustión de desperdicios, exigiría seguramente planes cuidadosamente estudiados. La única manera de evaluar adecuadamente las posibilidades prácticas que ofrecería tal solución consistiría en poner en servicio un conjunto de aparatos instalado a título experimental en una colectividad especialmente escogida; no obstante, es posible obtener una idea clara preparando una lista del consumo probable de energía y de la potencia necesaria en un caso imaginario. Es lo que trata de hacer el cuadro 2, donde las diferentes "cargas" enumeradas han sido calculadas para una colectividad de 40 o 50 familias aproximadamente, situada en una región soleada donde la velocidad del viento sea de 16 a 20 Km por hora.

Los autores están convencidos de que es posible utilizar económicamente los recursos energéticos locales, siempre que se ponga todo el cuidado necesario tanto en lo que se refiere a la instalación propiamente dicha como en los métodos que deban seguirse para su funcionamiento.

DISCUSSION

Dr. Ramdas. I would like to congratulate the authors of this paper on their fresh approach to the problem. Without creating water-tight compartments in regard to the utilization of wind and solar energy, they have put forward a properly synthesized and balanced use of wind, solar and fuel power so that between these sources the needs of a community may be satisfied. In India there is a continuous migration from the villages to the towns which will decrease only when life in the villages can have something approaching the amenities of city life. The ideas put forward suggest a healthy solution for this problem.

Dr. Kothavalla. The paper presented is of great interest and value, as it makes a practical approach to the problem by an integrated effort using sun, wind and vegetable waste. However, I have some serious misgivings with regard to the last source of energy production, vegetable waste. In the first place it is not clear to me what was meant by vegetable waste. The problems to be solved relate to arid and semi-arid areas, which are mainly rural areas where the first essential is to grow more vegetation. If by vegetable waste is meant the crop residues remaining to the farmer, there would be almost nothing available as the fodder and feed supply is quite inadequate for the number of cattle in the country. In fact, only 60 per cent of the fodder required is available today. On the contrary more vegetation is needed in the arid areas to provide a suitable fodder substitute, protection to men and beasts against the severity of weather and some fuel at a time when other sources are not available. Even supposing vegetable waste other than what could be used by cattle were available, the first claim on it would be for manuring the soil, as the Indian soils need as much humus as can be made available. Thus using vegetable waste as a source for obtaining energy which can be used for human requirements, is a proposition of doubtful value.

Mr. Dresden. I should like to support the author's theories that it would be worthwhile to start a test case. It has been said that the burning of vegetable waste is a pity. I cannot help thinking that the communities in question are today burning far more vegetable waste with far less comfort in return, than the authors plan for them. Of the total 129,000 kwh. available for their comfort, a maximum of 25,000 would come from this source; this would be far less, were the suggestion to cook in solar cookers followed. In any case, the suggested combination would mean a great saving. The test should mainly serve to find out in how far the farmer or his wife must be scientists (as Dr. Ramdas put it).

M. Aubert. Il est certain qu'il y a des cas où, comme l'a indiqué M. E. W. Golding, il reste, même dans les régions semi-arides ou arides, quelques déchets végétaux qui ne peuvent être utilisés, soit par l'intermédiaire d'animaux, soit par compostage, comme sources d'humus pour les sols. Ils doivent l'être, alors, comme combustibles. Cependant ils ne peuvent l'être qu'en très faible quantité.

Et nous ne devons pas oublier que si la tendance naturelle des habitants de ces régions est de détruire la faible végétation existante pour justement en utiliser les débris comme source d'énergie ou combustible de chauffage, c'est notre devoir à nous, chercheurs des zones arides, d'essayer de mettre au point

l'utilisation de sources d'énergie d'autres origines pour que les éléments végétaux puissent jouer au mieux leur rôle essentiel de protecteurs des sols et de sources d'humus.

Mr. White. This statement is both intriguing and provocative. It is intriguing because it suggests an integrated study of all energy needs in relation to all available energy sources in one community. It is provocative because it suggests that "the best—if not, indeed, the only—way to determine the practicability of such a scheme" is by moving ahead with one or two experimental installations. All of us here are interested in the possible service of international and interdisciplinary co-operation in dealing with research on arid zone problems. In view of the preceding discussion do the authors in fact believe that a field trial is the next desirable step? Or do they see other problems deserving attention in the laboratory before the field demonstration is launched? What is the most effective way of advancing the solution of this problem?

[Editor's note: At the concluding meeting of its eighth session, held in Bombay on 2 November 1954, the Advisory Committee on Arid Zone Research made the following recommendation: the committee recommended that the Director-General take steps to encourage one or more countries in initiating a pilot project for the integrated development of the energy resources of a small area, drawing if practicable upon the help of the Expanded Technical Assistance Programme (document Unesco/NS/121, recommendation 17)].

II

SOLAR ENERGY
ÉNERGIE SOLAIRE
ENERGÍA SOLAR

UTILIZATION OF SOLAR ENERGY

by

FARRINGTON DANIELS

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The sun is the original source of nearly all the work done for the human race. It has produced all our food and fuel. The industrialized nations, with heavy energy demands for manufacturing, trains, automobiles, and for house heating and cooling, can carry on their activities only because they are drawing heavily on the accumulated plant products of photosynthesis of long ago, which have been converted into coal, petroleum and natural gas. They are using up the capital in the bank. The rural areas, however, are living on current income of sunshine through agriculture and human and animal labour.

The industrial fuels have not been distributed equally among the nations of the world and the supplies will not last for ever.

But solar energy will be available in abundance as long as the sun shines and there are people to use it. We should not, however, wait for our great-grandchildren's problems. We have a challenge right now in many arid and semi-arid regions. If gasoline (petrol) has to be brought on camel-back for 500 km., it is —practically speaking—as unavailable as it will be in industrialized areas a few hundred years hence. For the sake of those who live in arid regions where sun and land are abundant and fuel is prohibitively high, we should try vigorously to find new ways of utilizing solar energy at once. This is not a local problem, it is one that affects the welfare and stability of the whole world.

The purpose of this conference, I assume, is to inquire into the possibilities of using solar energy directly in non-agricultural ways to do our work and to advance our material civilization in the non-industrialized areas, particularly in the arid and semi-arid regions of the world.

The problem is not to develop a solar engine or other device of high efficiency—it is to develop the most h.p. or the most kw. of electricity for a given investment of capital and a given burden of transportation.

In arid zones, the pumping of water from wells is an important contribution to the welfare of the community, and solar energy may be uniquely favourable for such a purpose. Its intermittency is no handicap for irrigation. Solar heating of houses and solar cooking are now possible, and they may be able to reduce the demand for fire materials, thus conserving the grass, shrubs and trees and decreasing soil erosion. Again, on farms and in villages, new sources of power can give electric lighting and greater comforts, as well as small new industries and increased economic production.

Almost no effort has been devoted to the direct utilization of solar energy. It is a technical and social problem where many sciences meet—chemistry, physics, engineering, meteorology, climatology, hydrology, ecology, and agriculture.

In considering any new development such as the utilization of solar energy, it is helpful to ask ourselves five questions: (a) Is it theoretically possible? (b) Is it technically feasible? (c) Is it economically sound? (d) Is it socially useful? and (e) Is it politically wise?

If a new development is socially useful as well as technically feasible, it may be politically wise to proceed with it at once, even if it is not economically self-supporting at first. I believe that the utilization of solar energy meets these requirements and that a programme of research and development should be initiated at once, starting in those areas which greatly need mechanical and electrical power in small isolated units. It must be made abundantly clear, however, that at the present moment there are no practical solar devices capable of competing with electric power lines and gasoline engines, where these are available. There is no era of solar prosperity just ahead—only, for later, hopes through research. But they are intriguing, challenging hopes. This conference can accomplish a great deal; first by arousing interest and encouraging new scientific and inventive talent to tackle the problems; second, by pointing out directions in which research should be encouraged and various ways in which solar energy can be used in non-industrialized areas; and third, by studying cost limitations which must be met under special conditions. The isolated semi-arid regions where fuel-powered engines are not now competing might well afford to pay a price high enough for applications of solar energy to justify starting soon. Such installations may become trial plants for more general use later in the more industrialized areas.

SOLAR ENGINES

Let us now examine more fully each of the five questions and their implications in relation to solar engines. Solar engines are by no means the most promising ways of utilizing solar energy. Other ways will be discussed later. Is the direct utilization of solar energy in engines theoretically possible? Yes. Heat can be made to do useful work and there is an abundant supply of solar heat. In India, I assume that an acre of land (67 m.^{2}) receives about 25 million kilocalories of heat from the sun each day. This heat is roughly equivalent to 100 million BTU, to the burning of 4 tons of coal or 12 tons of dry wood. It is equivalent to 29,000 kwh. of heat or 7,000 kwh. of electricity if it can be used in an engine of 25 per cent efficiency, or to 1,400 kwh. of electricity if used in an engine of 5 per cent efficiency. One kw. of work is equivalent to 1.3 h.p. and roughly equivalent to the work of a dozen men. This heritage of sunlight falls equally on good agricultural land and on wasteland. This heat energy is far more than would be required in any conceivable state of industrialization if ways can be found to utilize it effectively and practically. However, it must be emphasized that we are interested in the work which the sun can do, and the conversion of the sun's heat into work is at present difficult and inefficient.

Is the direct utilization of solar energy for operating engines technically feasible? Here the answer is yes, with reservations. In 1878 a printing press in Paris was run by solar energy. In 1913, water from the River Nile was pumped by solar engines for irrigation, and a mine in the United States was lighted day and night for many years by small electric lamps driven by a dynamo attached to a water wheel, and operated from a raised water tank which was filled during the daytime by means of a pump driven by a solar-heated steam engine.

Thus, solar engines can be built and operated, but they are inefficient and expensive. Sunlight is diffuse and must be collected over large areas to generate much power, and large areas of machinery or collectors or almost anything are expensive. In the United States an acre of glass or an acre of concrete might cost $10,000. Moreover, all heat engines are subject to a thermodynamic law, $\frac{T_2 - T_1}{T_2}$ according to which the fraction of the heat which can be converted into useful work depends on the magnitude of the difference in temperature between the hot and the cold parts of the engine, just as the work which can be obtained from falling water depends on the height through which it falls. Large lenses and mirrors can make possible the high temperatures needed for an efficient engine bu the types thus far used require expensive turning mechanisms for following the sun.

Are solar engines economically sound? The present answer has in industrialized countries, to be no. In those countries where technologies are most advanced, the fuel-powered engines are so cheap and so satisfactory that there has been no incentive for developing solar engines. But in sunny, non-industrialized regions, the possibility of competition with animal power is a challenge which this conference should face. The chance of success depends on the ability to design simple solar engines that are cheap enough per unit of power output. Low capital investment and low repair cost are far more important than efficiency. The solar heat available is so abundant that solar engines may be considered, even if the efficiency of conversion into work is very low. In regions where transportation costs are very high the initial solar equipment must be as light in weight as possible and, after installation, there must be no continuing cost for transporting fuel.

There is an important point here that I wish to stress for this conference. Engines and machines using fossil fuels have been developed by the scientists and engineers in industrialized countries, where fuel is abundant and cheap and technicians are available to install the machines and make repairs. High efficiencies are the goal there. Gasoline engines for automobiles, diesel engines for trains and large steam plants for generating electricity have been gradually increasing in efficiency, until any efficiency of less than 25 or 30 per cent is regarded as unprofessional and unacceptable. But let us here, in this conference, be content to start with solar machines which have a conversion into useful work of only 1-5 per cent of the sun's radiation which falls on a solar engine, and let us insist on a simple low cost engine, which does not need complicated repairs. Since we have an ample supply of sunlight "fuel" which is almost free, we can afford to use it less efficiently. Unfortunately no simple engine of this sort is yet available, but later on I would like to review the possibilities of simple solar engines, some of which might conceivably substitute thin plastics for expensive metals, and also to point out areas of research where new minds and fresh viewpoints are needed. I have for exhibition some transparent plastic sheets which may well be investigated. They are inexpensive because only a few hundredths of a millimetre thick. A mirrored surface of aluminium on one side of the plastic sheet is commercially available. It is hoped that several laboratories will test out this material for durability and practicality.

Let us consider setting up solar engines, first in places where the competition will not be with gasoline engines, steam plants and windmills, but with manpower and animal power. I have tried to collect data on the costs of small engines and windmills. Apparently, a small 2 h.p. engine costs about $75 in the United States of America and requires about a litre of gasoline per hour. The light-weight, portable air-cooled type will run about 1,500 hours before requiring repairs and complete overhauling. A water-cooled engine will run for about 5,000-10,000 hours before overhauling; an automobile engine may operate for about 2,500 hours without serious repairs. These normal lives should be compared with the lives of animals which do comparable work. In the United States of America a few years ago, the statistical time during which a farm horse worked was about 1,000 hours per year. I find that in some semi-arid regions a bullock costs about $150 to $200 and has an active life of about 6 or 7 years. A camel costs about the same amount.

The initial cost of tall windmills is greater, perhaps tenfold greater, than that of engines, but there is no fuel to buy and the repairs are negligible. However, a windmill is not practical unless the prevailing wind is perhaps 8-10 m.p.h. or more. In my state of Wisconsin, rural windmills were once very common—nearly every farm had a windmill—but they are now rapidly being replaced by rural electrification which costs about 3 cents per kwh.

In large installations, electric power plants can be built in the United States of America for about $150 per kw., and the electricity can be carried by high voltage lines for distances up to about 300 miles. The cost to large industries using electricity in quantity is only a few tenths of a cent, although for small and widely dispersed users the cost is of course much greater.

In any consideration of costs, it is well to remember that the continuing purchase of gasoline or electricity requires some type of cash crop which must be sold to pay for the source of power delivered from outside the community, whereas in a self-contained, rural economy the crops fed to work animals, the sun's radiation operating a solar engine or solar battery and the wind operating a windmill do not call for the continuing payment of any money or exchange of goods beyond the local community.

The utilization of solar energy would be socially useful because the creation of greater wealth through larger sources of power usually leads to higher material standards in a way; and the release from excessive manual labour leaves men freer to devote their time to more intellectual matters.

Solar energy, if it can be brought into use, will have another social value in agricultural areas, where it could liberate land for human use. Let us imagine that a cheap solar engine can be developed, perhaps with thin plastics and a minimum of metal, capable of replacing an animal for lifting water for irrigation and at an initial cost not much greater than that of the animal. Even if the solar engine is only 1 per cent efficient, 1,000 sq. ft. (about 100 m.^{2}) of sunshine would give the equivalent of one h.p. This area is not larger than that needed for the work animal as he walks around the well from which the water is being raised —and the number of work animals could then be reduced and good agricultural land needed for feeding the animal would become available instead for feeding the animal's keeper and his family.

Finally, is it politically wise to develop solar energy? I believe that it is both wise and important. In the non-industrialized nations which are far from coal deposits, petroleum supplies or electric power lines, the governments might well afford to subsidize the development of new sources of power. If solar engines are developed they can be made in small units, with costs which are small in comparison with hydro-electric plants and nuclear power reactors.

The nations which have become industrialized earlier will be glad to help in the development of more mechanical and electrical power in countries which desire it. Time was when nations could live in isolation, not knowing about the economic, social and political welfare of other nations. With modern transportation and rapid communications such times have gone forever.

SOLAR ENERGY RESEARCH

In the preceding section the development of solar engines was stressed, but solar engines are only one of several possibilities in the utilization of solar energy —and probably one of the least promising ones.

Large, efficient solar engines are quite a long way off, but there may be an important place for small, cheap, and relatively inefficient engines. The direct utilization and storage of solar heat for houses is already here. Domestic hot water production and cooking with the sun have been well established. The distillation of fresh water from sea water does not seem to be too far from practical realization. The long-range hope of using the sun's radiation directly lies in photoelectricity and in photochemistry. These photo-problems are difficult to solve but nature has provided us with the accomplishment of photosynthesis as an inspiration for further improvements. Agriculture can be considerably increased in efficiency and the actual storage of solar energy in plants is remarkable, but the efficiency is not apt to be increased to more than a few tenths of 1 per cent of the sun's total radiation stored in the form of usable chemical energy. Mass culture of algae or rapidly growing plants in plastic bags offers some promise, particularly in water-scarce areas. The best approach thus far appears to lie in photoelectricity produced in special crystals by sunlight.

SPACE HEATING AND COOLING

The heating of houses should be one of the easiest ways of turning solar energy into practical use. Here the high temperatures so important for operating solar engines are not necessary. In the United States of America only a very few houses use the sun alone for their heating systems, but it has been predicted that 13 million houses will be solar-heated by 1975. Activity along this line will, however, have to be markedly accelerated if this prophecy is to be fulfilled.

Three general methods have been explored for storing the sun's heat for night-time and for cloudy weather—hot water tanks, melting of chemical compounds or salt hydrates, and pebble beds through which air is blown. Three groups in the United States of America have been prominent in this pioneer work—Professor H. C. Hottel, Dr. Marie Telkes and Mr. G. O. G. Löf. A house has been built by Dr. Telkes in which heat sufficient for ten days may be stored with the help of large quantities of sodium sulphate. This salt is dehydrated above 32.2° C. but below this temperature it combines with 10 molecules of water with the evolution of heat, and maintains a temperature of about 32.2° C. This house has been through three winters in Massachusetts. In the pebble bed method for heat storage air is passed through solar-heated absorbers and through a mass of small stones 1 or 2 cm. in diameter contained in an insulated box buried in the ground. The heat exchange between a gas stream and a pebble bed is very rapid and large quantities can be stored, to be used when needed by turning valves, so that the air of the house is circulated through the warm pebble bed.

Hot water collection of heat, perhaps in plastic absorbers, and storage in large insulated tanks of special design, offers some promise. Further research is needed on all three methods.

This conference, I assume, is more interested in cooling houses than heating them, and solar energy is, in principle, capable of doing this also, although it is more difficult. A simple type of cooling could be devised for use in some areas where the nights are cool, by blowing outside air through a pebble bed at night and recirculating the air of the house through the cooled pebble bed during the day. Research might indicate a way to cool the night air still more by means of devices to radiate heat to the night sky. A small amount of mechanical or electrical power is required for circulating the air. A pebble-bed cooler might well be tried out in hot, arid regions in the hope that an inexpensive installation could reduce partially the discomfort of the hottest part of the day even if it does not give complete air-conditioning.

Solar energy has already been put to work in houses for cooking and for supplying hot water for domestic use. The chief contribution to solar cooking has been made by the scientists of India. Possibly further research may show that mirrorized plastics can be used to give a cheaper solar cooker. In California hot water heaters have been installed with blackened pipes on the roof and insulated storage tanks. Brooks in California and Heywood in London have made significant studies of solar water heating.

It is hoped that this conference will be able to point out areas where the social and economic conditions are such as to justify experimental developments on solar house heating. How low in cost and upkeep must a house heating or cooling unit be in order to meet practical consideration? Are there areas, now uninhabited, which could support settlement in the case of the extremes of heat and cold in houses being partially eased through new applications of solar energy? If so, scientists and engineers should explore all relevant aspects of research.

DISTILLATION OF SEA WATER

The solar evaporation of sea water to give salt is one of man's oldest industries. New improvements are still being made, as in the addition of a trace of a coloured dye to increase the absorption of solar radiation and reduce the reflection losses from the salt. The recovery of pure water is a much more difficult problem, but the problem is being attacked. Three different approaches will be described later in the special sessions. Are there areas near the ocean where crowded cities, or new cities yet to be built, could afford to pay a premium price for fresh water, solar-distilled from the ocean or salt seas? If such developments became possible, sea-coast cities would not, as now, usually have to be located by rivers. A large area of low-lying, flat land adjacent to the salt water would be required, however. Again, are there agricultural regions adjacent to the sea which might be opened up to settlement if sun-distilled water can be obtained at a price considerably above irrigation water in other areas?

SOLAR ENGINES

A few small engines have been built. Dr. Abbott, of the Smithsonian Institution, who has long been a pioneer in this field, has a design for a 2 h.p. engine with a parabolic mirror 10 ft. in diameter which he could build at once. The sun's heat rays are focused on to a small vacuum-jacketed Pyrex boiler containing a high-boiling liquid. He believes that the initial cost of mass-produced engines would be about $1,000.

Large mirrors are subject to wind damage and dependent on turning mechanisms to keep them pointing toward the sun, but they can give high temperatures in direct sunshine with fairly efficient operation. Other solar engines of this type will probably be described in this symposium.

Another type of solar engine uses "hot boxes" with several glass plates for its collecting area. Temperatures well above that of boiling water can be obtained with them, and the initial cost will probably be less. Moreover, the engine can operate in partly cloudy weather, because focusing is not essential, but the efficiency is considerably less than that of the engines using focused radiation.

The principle of the hot box multiple-glass plates is important for all heat collectors. The sunlight passes through the transparent glass and heats up the absorbing material behind it. This heated receiver behind the glass would lose an appreciable fraction of its heat through back radiation in the long infrared, but the glass plates which are opaque in the infrared beyond 2.5 μ reduce this radiation loss. The plates also reduce the loss of heat by the movement of the surrounding air.

An intermittent type of solar engine should be investigated in which many large tubes filled with a light-absorbing gas are arranged to expand and contract with alternating periods of light and shade.

Further research and new ideas are needed for the development of cheaper and better collectors. A supply of cold water or other cooling medium is necessary for the operation of these low-temperature solar engines, in order to maintain a temperature difference of sufficient magnitude for reasonable efficiency. Snow banks on mountains or permafrost in the arctic regions offer possibilities for low temperature operation.

SOLAR FURNACES

Despite the handicap of low temperature in solar engines, for experimental purposes solar furnaces can give higher temperatures under more desirable conditions than any other type of furnace. Very large mirrors focusing on to small areas have given temperatures up to 3,000° C. under conditions free from the contaminations which often accompany the heating of furnaces with fuel or electricity. Such furnaces are finding important use in studying the physical and chemical properties of refractories and other materials at extremely high temperatures. Trombe in France has done important work in this field.

PHOTOSYNTHESIS

Nature has shown us through photosynthesis in plant growth that solar energy can be utilized through photochemical reactions. The theoretical limitation in the efficiency of heat engines does not apply in chemical reactions but there are other limitations. Experiments over many years at the University of Wisconsin show that, under ideal laboratory conditions, with algae about 30 per cent of the absorbed light can be stored as chemical energy. An average agricultural crop has an efficiency far less than this, and stores only a few tenths of 1 per cent of the sun's energy which falls on the growing crops. Interesting experiments have been carried out in California, at Boston and particularly in Japan on the mass culture of algae, which indicate that it may be possible eventually to obtain yields of organic material which are perhaps 10 times as large as the yields obtained by ordinary agriculture in the temperate zones. There are problems of bacterial contamination, filtering difficulties and high capital investment, but the possibilities in food, even if not in fuel, merit expanded research. Attempts have been made to grow algae in plastic tubes on a mass production basis. Similar experiments with small plants might be carried out in arid regions without soil, using the plastic covering to conserve the water and nutrients.

PHOTOCHEMISTRY

There should be photochemical reactions other than the combination of water and carbon dioxide in photosynthesis by means of which the sun's energy can be stored and converted later into useful work. They must meet very special requirements, and only a very few are available in which the molecules are broken up into smaller parts with the absorption of heat. When these recombine they give back the original heat of dissociation, but unfortunately in most reactions of this type the recombination is very rapid—often practically instantaneous, so that there is no chance of storing the energy.

One interesting reaction is the photo-decomposition by ultra-violet light of water into hydrogen and oxygen in the presence of cerous and ceric salts, reported by Heidt at the Massachusetts Institute of Technology. These two gases could be stored and reunited to give heat later at a high temperature. There is very little ultra-violet light in sunlight and the reaction has been carried out in the laboratory only in micro quantities; but the principle is sound. Chemists throughout the world should try to find some new, favourable compound which will absorb sunlight over a wide range of wavelengths and obtain products which can be recombined when needed at a later time in such a way as to give back the energy which went into the original photochemical reaction. This might involve a delayed reversal of the reaction or the formation of a product which would react later with air. Air is just as free as sunshine. No suitable compound is in sight now (other than the chlorophyll used in photosynthesis in living plants), but there is no obvious reason why possibilities should not be explored among coloured organic, or inorganic, compounds; or even among coloured crystals.

PHOTO PRODUCTION OF ELECTRICITY

Photo-galvanic cells are theoretically possible in which compounds are broken up by sunlight into fragments that are electro-chemically charged because of the presence or absence of electrons. These fragments usually recombine instantaneously, but if they are relieved of their electrical charges they may be kept from rapid recombination. By placing metallic electrodes in the solutions these charges can be removed and the resulting electrons are caused to flow through the wire from one electrode to the other. This flow gives a current of electricity which can, in principle, be used directly to run a motor. A little exploratory work has been done by Rabinowitch and others on these photo-oxidation and photo-reduction cells. There should be more such work done in this field.

Another proposal involves thermo-galvanic cells with one electrode in the sun and the other in the shade.

Thermopiles with junctions of unlike metals can produce electricity by putting one junction in the sun and the other in the shade. Ordinarily the efficiencies are quite low but values up to a few per cent have been reported. The higher efficiencies have, however, been obtained with alloys which are not very permanent.

One of the most hopeful approaches to the utilization of solar energy is that of the photo generation of electricity in solids, which are semi-conductors of electricity. Surfaces of copper and copper oxide, selenium, cadmium sulphide and silicon have been used. A very promising cell of this type consists of a thin surface of silicon of extreme purity to which has been added controlled impurities of boron. It has been developed recently by the Bell Telephone Laboratory with a 5 per cent efficiency in the conversion of sunlight, giving a calculated production of 50 w. per square yard. It is hoped that rapid progress will be made in these solar batteries.

STORAGE OF INTERMITTENT POWER

Since sunlight is available for only part of the day, it is necessary for many purposes to provide storage facilities. The storage of heat has been discussed already. The storage of power is expensive. Water can be pumped to a higher reservoir while the sun is shining and allowed to flow back later through a water wheel that drives a dynamo. If there is a hydro-electric plant nearby the solar power could be combined with it, and the solar engine used to replace the water turbine during the daytime and thus conserve the water supply. A high plateau for a reservoir, an abandoned mine, or a diving-bell in the ocean could be used also. One must remember, however, that means for holding large volumes of water are very expensive. Integration with an electrical power grid can minimize the handicap of intermittency. Coal as well as water can be saved while a solar engine is operating.

Storage batteries provide a good means of storing electrical energy, but something cheaper and better than the automobile lead storage battery is needed. Intensive research on new types of storage batteries or their equivalent is nearly as important as research on the production of solar power.

Electrical storage batteries for solar energy do not need to be immediately reversible, small and portable. Some efficient electrochemical process, such as that involved in the deposition of aluminium, might be used. The aluminium could be made up into electrochemical batteries to be discharged at a later time, and the aluminium could, in principle, be recovered later by electro-deposition from the aluminium salts produced in the operation of the battery.

MISCELLANEOUS APPLICATIONS

It is hoped that many other possible applications of solar energy will be brought to the attention of this conference. Among these might be included inexpensive, low efficiency, steam engines operating on wood and agricultural waste. Again, these fuels may be heated with an insufficient supply of air to give carbon monoxide and hydrogen, which in turn can be used in "fuel cells", in which the gases are bubbled over one electrode in a bath of a fused salt and oxygen is bubbled over the other electrode. Promising laboratory experiments on the direct production of electricity by this method have been carried out in Holland, England and the United States.

Agricultural areas in extreme northern and southern latitudes can perhaps be extended by the use of coal dust to hasten the melting of snow from the sun's radiation in the spring, and by devices which use solar heat to delay the time of frosts in the autumn. Here again, it is important to encourage more research.

CONCLUSIONS

Although the direct utilization of solar energy in non-agricultural ways is only in the research stage, it offers large potentialities for improving economic and social conditions. Scientists and engineers are urged to turn their talents toward research and development in this field.

Economic competition with coal and petroleum in industrialized countries will be difficult, and the first developments will have to come in small isolated units where electrical power is not available and where transportation costs for gasoline are excessive. Inexpensive solar devices are needed, even if they are not very efficient.

Among the more promising applications of solar energy are the heating and cooling of houses and the distillation of fresh water from sea water. Here rapid progress may be expected.

Photochemistry offers much hope for long range development and the existence of photosynthesis in nature acts as an encouragement for intensive photochemical research.

Important progress has been made in the direct conversion of sunlight into electricity in crystalline semi-conductors.

In conclusion, it may be said that the arid and semi-arid regions of the earth offer ideal opportunities for developing the utilization of solar energy. It is hoped that this conference will direct the attention of investigators throughout the world to important areas of research which may lead to practical uses of the sun's energy.

UTILISATION DE L'ÉNERGIE SOLAIRE

par

Farrington Daniels

RÉSUMÉ

L'auteur commence par montrer que l'énergie solaire fournit *a*) des denrées alimentaires par photosynthèse et *b*) des combustibles, aussi par photosynthèse, mais dans la nuit des temps. Toutefois comme les seconds ne sont pas inépuisables, il est indispensable de découvrir de nouvelles sources d'énergie. Étudiant les différents aspects de l'exploitation de l'énergie solaire, l'auteur pose les cinq questions suivantes : Cette exploitation est-elle théoriquement possible, techniquement praticable, économiquement judicieuse, socialement utile et politiquement sage? Théoriquement, il est possible d'utiliser l'énergie solaire, puisqu'un appareil n'ayant qu'un rendement de 5 % pourrait tirer 3.750 kWh de la quantité de chaleur reçue chaque jour par un hectare de terre, en Inde par exemple. La chose serait techniquement possible, sauf que les moteurs solaires sont coûteux et d'un mauvais rendement. De plus, ils sont soumis au principe de la thermodynamique selon lequel le rendement d'une machine thermique est fonction de la différence de température entre source chaude et source froide, d'où une réponse, sur le plan économique, négative, du moins à l'heure actuelle et dans des conditions courantes. Au contraire, les moteurs solaires pourraient avoir un intérêt économique dans des régions ensoleillées et non industrialisées, où ils n'entreraient en concurrence qu'avec le travail humain ou animal et non avec des moteurs à essence ou à vapeur ou avec des éoliennes. De toute manière, les constructeurs de moteurs devraient rester modestes et ne pas rechercher un rendement qui dépasse 1 à 5 %. L'auteur cite ensuite les prix de revient de différents moteurs et éoliennes. Il ne faut pas perdre de vue qu'un achat régulier d'essence ou d'électricité suppose une culture de rapport qui en donne les moyens. En outre, l'énergie solaire aurait une valeur sociale, puisqu'elle permettrait de décharger l'homme de tâches exagérément pénibles et pourrait être utilisée partout sous forme de petites installations. Elle permettrait également de récupérer des terres arables, par suite de la réduction du cheptel de travail. Enfin, du point de vue politique ce serait aussi une mesure judicieuse car de nouvelles sources d'énergie à bon marché apportent richesse et prospérité à la population.

L'auteur décrit ensuite différents moyens de tirer parti de l'énergie solaire. Avant que ce problème puisse être complètement résolu, il faudra cependant réunir des données plus complètes sur le rayonnement total moyen, ses écarts par rapport à la moyenne, la fréquence des jours nuageux, la variation du rayonnement sur de petites surfaces et son absorption par des collecteurs inclinés à des angles différents. D'ores et déjà, l'énergie solaire sert au chauffage et à la réfrigération des habitations.

Quant à l'accumulation, trois principaux procédés ont été expérimentés pour assurer le fonctionnement des installations, la nuit ou par temps bouché. L'un se fonde sur l'emploi de réservoirs d'eau chaude, l'autre

sur la dissolution de composés chimiques ou d'hydrates de sels et le troisième sur la circulation d'un courant d'air puisé à travers des lits de gravier.

Il est également possible de réfrigérer des locaux d'habitation aux heures où le soleil est le plus chaud par un procédé qui consiste à faire évaporer par chauffage un gaz dissous (de l'ammoniaque par exemple), puis à le condenser; le refroidissement se produit lorsque le liquide se vaporise pour être ensuite réabsorbé par la solution refroidie. Des fours solaires ont également été mis au point par des savants indiens. Il serait nécessaire d'étudier les conditions qui justifieraient de nouvelles recherches expérimentales sur l'application de l'énergie solaire aux usages domestiques (chauffage et cuisine) dans certaines régions. La distillation de l'eau de mer au moyen de l'énergie solaire constitue un autre sujet de recherches. Ce sont les moteurs solaires conçus sur le principe du "piège à calories" (*hot box*) qui offrent les plus larges possibilités de perfectionnement. Grâce aux fours solaires, il est devenu possible de faire des recherches sur les propriétés physiques et chimiques des matériaux à des températures extrêmement élevées. On pourrait aussi intensifier l'utilisation de la photosynthèse (c'est-à-dire du procédé employé par la nature pour emmagasiner l'énergie solaire), sous forme de culture d'algues à grande échelle et d'étudier la possibilité d'une accumulation de chaleur solaire grâce à d'autres réactions photochimiques, par exemple celle que Heidt a découverte à l'Institut de technologie du Massachusetts et qui consiste à décomposer l'eau en oxygène et hydrogène par la lumière ultra-violette en présence de sels céreux et cériques. Il faut également pousser plus loin les recherches sur la production de photo-électricité au moyen de cellules à photo-oxydation ou photo-réduction. Les cellules thermo-galvaniques du genre de celle qui a été récemment mise au point par les laboratoires des téléphones Bell offrent une autre solution. L'un des plus durs problèmes est celui de l'accumulation de l'énergie obtenue. Un nouveau type d'accumulateur — non immédiatement reversible, petit et portatif — pourrait être mis au point.

Toutes ces applications de l'énergie solaire — et d'autres encore — devraient faire l'objet de nouvelles recherches approfondies.

UTILIZACIÓN DE LA ENERGÍA SOLAR

por

Farrington Daniels

RESUMEN

El trabajo comienza indicando que la energía solar nos suministra: *a*) substancias alimenticias por fotosíntesis; *b*) combustibles, también por fotosíntesis, pero que tuvo lugar en tiempos remotos. El autor señala que como esos productos no son inagotables deben encontrarse nuevas fuentes de energía. Los factores que intervienen en la utilización de la energía solar, aparecen estudiados en relación con cinco preguntas: ¿Es esa utilización teóricamente posible, técnicamente factible, económicamente acertada, socialmente útil y políticamente sensata? Desde el punto de vista teórico la utilización de la energía solar sería factible, ya que un motor de un rendimiento del 5 % podría producir 3.750 kWh de electricidad del calor recibido diariamente en una superficie de una hectárea en la India, por ejemplo. Si bien ello sería técnicamente factible, los motores solares tienen poco rendimiento y son caros. Además, hay limitaciones impuestas por las leyes termodinámicas, ya que el rendimiento de un motor térmico depende de las diferencias de temperatura entre las partes calientes y frías del motor. Esas consideraciones indican que su aspecto económico es negativo. En circunstancias ordinarias, los motores solares son en definitiva antieconómicos; pero en regiones soleadas no industrializadas, donde la única fuente de energía es el esfuerzo muscular, humano o animal, podrían ser económicamente aceptables. Los constructores de esas máquinas no deberían buscar un rendimiento elevado y contentarse con motores de un rendimiento de un 1 a un 5 %. En este trabajo se indican los precios de diversos motores y molinos de viento. No debe olvidarse que la compra regular de

gasolina o de electricidad supone la existencia de un tipo de cultivo que rinda los fondos necesarios. Además, la energía solar es socialmente útil porque su utilización reduciría el excesivo trabajo humano y porque los motores reducidos de ese tipo pueden emplearse en cualquier lugar. Además, al disminuir el número de animales de tiro podría aumentarse la superficie labrada para obtener cosechas para el consumo humano. Políticamente también sería sensato utilizar la energía solar porque las nuevas y económicas fuentes de energía llevan aparejadas riqueza y prosperidad.

El estudio incluye luego una descripción de los medios para utilizar la energía solar. No obstante, antes de que pueda resolverse completamente ese problema es necesario disponer de información más completa sobre el promedio de radiación, las desviaciones respecto a ese promedio, la frecuencia de los días nublados, la variación en pequeñas zonas y la absorción por aparatos colectores de diferente inclinación. La energía solar se utiliza ya para la calefacción y refrigeración de las habitaciones. Los tres métodos principales ensayados para almacenar el calor solar y utilizarlo durante la noche y en días nublados se basan en el empleo de depósitos de agua caliente, en la disolución de productos químicos o sales hidratadas y haciendo pasar una corriente de aire a través de una capa de guijarros. Para refrigerar las casas en las horas de mayor intensidad solar se puede evaporar un gas como el amoníaco mediante el calor y condensarlo luego por enfriamiento. Se consigue refrigerar el aire vaporizando el líquido para ser reabsorbido luego en la solución al haberse enfriado. Los hombres de ciencia indios han ideado y construído una cocina solar. Convendría averiguar en qué condiciones sería justificado realizar otros trabajos experimentales sobre el empleo de la energía solar para la calefacción de las casas y la cocción de los alimentos en algunas regiones. Otro problema que merece ser estudiado es la destilación del agua marina por medio de la energía solar. Los motores solares que trabajan basándose en el principio de la "trampa de calorías" *(hot box)* son los que ofrecen las mayores posibilidades de perfeccionamiento. Los hornos solares han permitido hacer investigaciones sobre las propiedades fisicoquímicas de materiales a temperaturas elevadísimas. La fotosíntesis, que es el medio natural de acumular energía solar, podría utilizarse de una manera más intensiva mediante el cultivo en masa de las algas. También debería estudiarse la posibilidad de descubrir otras reacciones fotoquímicas que acumulen la energía solar: por ejemplo, la reacción descubierta por Heidt en el Instituto de Tecnología de Massachussettss, según la cual los rayos ultravioletas descomponen el agua en hidrógeno y oxígeno en presencia de sales cerosas y céricas. Convendría también realizar más investigaciones sobre la producción de fotoelectricidad por medio de células de fotooxidación y fotorreducción. Las células termogalvánicas, como las descubiertas por los Bell Telephone Laboratories ofrecen otra posibilidad. La acumulación de la energía obtenida es uno de los más graves problemas. Debería estudiarse un nuevo tipo de acumulador que no sea inmediatamente reversible, de tamaño reducido y portátil.

Esas y otras aplicaciones posibles necesitan ser objeto de una investigación intensiva.

DISCUSSION

Mr. **Dresden.** It may seem curious that a rainy country like the Netherlands, actually having 200 days of rain a year, should work on harnessing solar energy, but there is a group of scientists, under Professor Wassnik in Wageningen, doing promising work on algae. I should like to establish a contact between Professor Wassnik and his group and Mr. Daniels, and that is what I plan to do.

Mr. **Daniels.** Dr. Young asked about the type of plastic exhibited and its properties.

The samples of plastic passed around are known as "mylar". This is a new plastic just being put on the market. It is unusually transparent in the visible and ultra-violet. It is probably rather transparent in the infra-red. Perhaps research should be encouraged in attempting to find a coating which would make it more opaque in the infra-red so as to serve as a better heat trap.

The length of life under exposure to bright sunlight should be tested in several different laboratories.

The second sample is mirrorized with aluminium vapour. It is just beginning to be produced in quantity.

THE DISTRIBUTION OF SOLAR RADIATION OVER THE EARTH'S SURFACE

by

J. N. BLACK

While the importance of solar radiation as a factor in the natural environment is now becoming increasingly appreciated, full consideration of its role in the development of systems of land use throughout the world is still hampered by the lack of knowledge of its global distribution. This is due in general to the difficulty of measuring incoming radiation; in the present investigation it has been possible to collect records of radiation received on a horizontal surface only for about 150 meteorological stations. The distribution of these stations leaves much to be desired from the climatological viewpoint, as more than 75 per cent of them are located in either North America or Europe; there is none in South America and only one in Asia. It was clearly impossible to attempt to map the distribution of incoming solar radiation from the directly observed data, and some other approach appeared to be necessary.

It has long been known that a relationship exists between radiation received at the earth's surface and either the duration of sunshine or the mean cloudiness. This was first suggested by Angstrom [1][1] who found that for Stockholm

$$Q = Q_o \left(0.25 + 0.75 \frac{n}{N}\right) \quad . \quad . \quad . \quad (1)$$

where Q is the radiation actually received, Q_o is the radiation income on a clear day, *n* is the actual duration of sunshine, N is the maximum possible duration of sunshine.

This relationship and the corresponding relationship where mean cloudiness is substituted for $\frac{n}{N}$ have recently been examined in detail by Berg [2], who showed that as a result of the departures from the strictly linear relationship at low values of $\frac{n}{N}$, or high values of cloudiness C, their use should be restricted to the calculation of mean monthly values only.

The same principle has been extended [3] to an examination of the relationship between Q, Q_A and $\frac{n}{N}$, where Q_A is the theoretical value of radiation to be expected if the atmosphere were perfectly transparent, using the values of Angot [4]. This procedure permitted an examination of the global distribution of incoming radiation, since, unlike Q_o, values of Q_A are immediately available for any part of the world and for any time of the year. Analysis of the Q, Q_A and $\frac{n}{N}$ data for 32 stations for which 12 monthly values of Q and $\frac{n}{N}$ are available established the relationship

$$Q = Q_A \left(0.23 + 0.48 \frac{n}{N}\right) \quad . \quad . \quad . \quad (2)$$

This equation was considered to be of general application over a wide range of latitudes, but unfortunately it did not prove possible to use it in determining the global distribution of solar radiation, since comprehensive and widespread records of the duration of bright sunshine are not available. It was therefore decided to examine the relationship between Q/Q_A and cloudiness C, using for values of C the maps prepared by C. E. P. Brooks for the second volume of Napier Shaw's *Manual of Meteorology* [5]. Of the 150 stations for which records of incoming solar energy are available, 88 were found to provide mean monthly values over periods of more than three years, and only these were accepted. Values of C for these stations were read off the maps and the following relationship was obtained by regression analysis:

$$Q = Q_A (0.803 - 0.340C - 0.458C^2) \quad . \quad . \quad . \quad (3)$$

where Q is the radiation actually received, Q_A is the potential radiation (Angot's value) and C is the mean cloud amount in tenths. A slide illustrating the data and the fit of the regression will be projected.

At this stage it is necessary to observe that a number of errors may be included in the calculation of equation (3) above. These may be grouped under several headings:

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[1] The figures in brackets refer to the bibliography on page 143.

1. Possible sources of error in Q data:
   (a) Mean monthly values are calculated for each station for the maximum number of years for which records are available, which is not the same in each instance;
   (b) The records for different stations refer to different periods of time, and not all stations are still maintaining records;
   (c) Different instruments, possibly varying in sensitivity, have been used at various stations;
   (d) Variations in the altitude of the stations have not been taken into account.
2. Possible sources of error in C data:
   (a) Although based on a large number of observations, the maps of C are generalized and smoothed: the Q/Q_A: C relationship may therefore be incorrect for some individual stations, since local topographical variations in C are not taken into consideration;
   (b) Errors may arise in interpolation between Brooks' isopleths of C.

In spite of these possible sources of error, the relationship appears to be satisfactory and is highly significant at 0.1 per cent probability. It was therefore taken as the basis for the calculation of radiation income, and values of Q were determined for each 5° intersection of latitude and longitude over land, and each 10° intersection over sea. These values were plotted on outline maps and the isopleths of radiation income were drawn. The unit of energy used is the mean daily radiation, in gram calories per cm.^{2} received on a horizontal surface, for each month. Twelve such maps—one for each month—have been drawn and have been made into slides for projection.

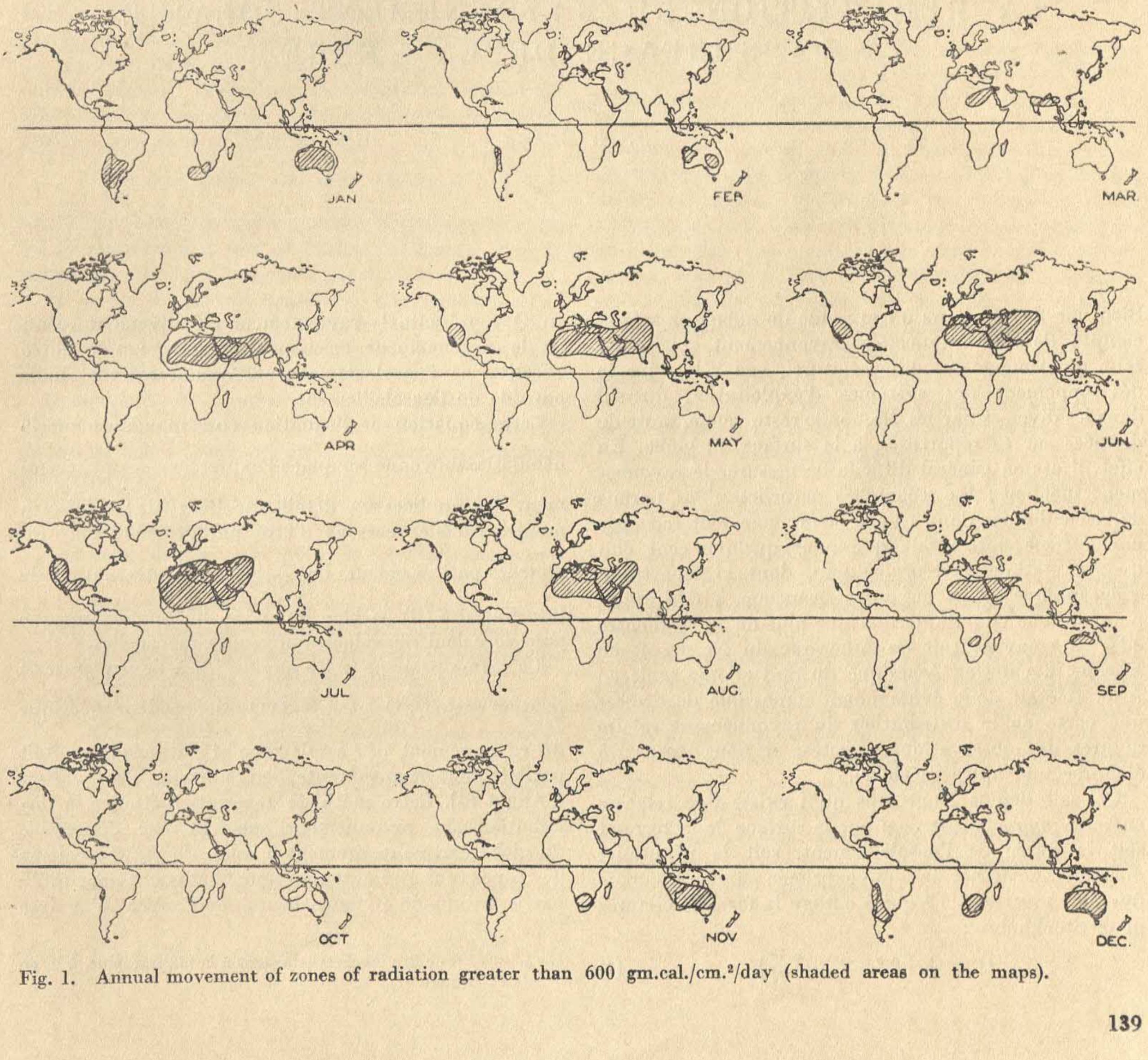

Fig. 1. Annual movement of zones of radiation greater than 600 gm.cal./cm.^{2}/day (shaded areas on the maps).

Certain features of these maps are not unexpected: the occurrence of the zones of high radiation at approximately 20°-30° of latitude: the parallel isopleths in the winter hemispheres compared with the more complicated pattern in the summer hemispheres: the higher values over land than sea at the same latitude, resulting from the greater mean cloudiness over the sea: the presence of zones of low radiation associated with the summer monsoon conditions where these occur: and the tendency for Australia—for example—to show two zones of maximum radiation, consequent upon the greater cloudiness over the mountain ranges of the centre. The data from these maps can be brought together to show the movement of these zones of high radiation throughout the year, by simplifying the maps to show only the areas of radiation greater than 600 gm.cal./cm.²/day, and mounting these simpler maps side by side: this has been done and the slide so made will be projected. As anticipated, these zones tend to move north and south with the sun, and show a high degree of correspondence with the distribution of the major arid zones of the world.

While the work on solar radiation undertaken at the Waite Institute has been directed to a better understanding of plant environment, principally in relation to evaporation and studies in crop physiology, it is hoped that these maps may be of interest to those concerned with other aspects of solar radiation.

LA RÉPARTITION DU RAYONNEMENT SOLAIRE A LA SURFACE DE LA TERRE

par

J. N. Black

Bien que de nos jours on se rende de mieux en mieux compte de l'importance du rayonnement solaire en tant qu'élément du milieu naturel, son rôle dans le développement des systèmes d'exploitation du sol dans les diverses parties du monde reste vague, faute de données sur sa répartition à la surface du globe. En effet, il est en général difficile de mesurer le rayonnement incident ; les recherches actuelles n'ont permis de recueillir des données sur le rayonnement reçu par une surface horizontale que pour quelque cent cinquante stations météorologiques, dont la répartition géographique laisse en outre beaucoup à désirer du point de vue climatique, puisque plus de 70 % d'entre elles se trouvent soit en Amérique du Nord soit en Europe, aucune en Amérique du Sud et une seule en Asie. Il était donc évidemment impossible de dresser une carte de la distribution du rayonnement solaire d'après des observations directes, et nous avons dû élaborer une autre méthode.

On sait depuis longtemps qu'il existe une relation entre le rayonnement reçu par la surface de la terre et soit la durée de l'ensoleillement, soit la nébulosité moyenne. Cette notion a été exprimée pour la première fois par Angstrom [1][1] qui a obtenu la formule ci-après pour Stockholm :

$$Q = Q_o \left(0{,}25 \times 0{,}75 \frac{n}{N}\right) \qquad (1)$$

où Q représente le rayonnement effectivement reçu ; Q_o le rayonnement reçu par ciel clair ; n la durée effective de l'ensoleillement et N la durée maximale possible de l'ensoleillement.

Cette équation et l'équation correspondante où la nébulosité moyenne remplace l'expression $\frac{n}{N}$ ont récemment été étudiées en détail par Berg [2] ; celui-ci a montré qu'elles cessent d'être parfaitement linéaires pour les petites valeurs de $\frac{n}{N}$ ou les valeurs élevées de la nébulosité (C), si bien qu'on ne doit les utiliser que pour le calcul de valeurs moyennes mensuelles.

Le même principe a été étendu [3] à l'examen de la relation entre Q, Q_A et $\frac{n}{N}$, où Q_A est la valeur théorique du rayonnement qui serait reçu si l'atmosphère était parfaitement transparente, en partant des chiffres d'Angot [4]. Cette méthode a permis d'étudier la distribution du rayonnement incident sur l'ensemble du globe car, contrairement à celles de Q_o, les valeurs de Q_A peuvent être obtenues immédiatement pour toute partie du monde et toute époque de l'année. L'analyse des données Q, Q_A et $\frac{n}{N}$ obtenues pour trente-deux stations où les douze valeurs mensuelles de Q et $\frac{n}{N}$ sont connues a permis d'établir la relation suivante :

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[1] Les chiffres entre crochets renvoient à la bibliographie, à la fin de ce rapport.

$$Q = Q_A \left(0{,}23 + 0{,}48 \frac{n}{N}\right) \qquad (2)$$

Cette équation a été considérée comme généralement applicable sous des latitudes très diverses ; malheureusement il n'a pas été possible de s'en servir pour déterminer la distribution du rayonnement solaire sur l'ensemble du globe, faute de disposer de statistiques complètes, dans le temps et dans l'espace, sur la durée de pleine insolation. En conséquence, il a été décidé d'étudier la relation entre Q/Q_A et la nébulosité (C), en prenant pour valeurs de C celles qui figurent sur les cartes établies par C.E.P. Brooks pour le deuxième volume du manuel de météorologie de Napier Shaw [5]. Sur les cent cinquante stations pour lesquelles on dispose de relevés d'énergie solaire incidente, quatre-vingt-huit pouvaient fournir des valeurs mensuelles moyennes sur des périodes de plus de trois ans ; seules, ces dernières ont été retenues. Les valeurs de C dans ces stations ont été prises sur les cartes et la relation ci-après a été obtenue par analyse de régression :

$$Q = Q_A \,(0{,}803 - 0{,}340\ C - 0{,}458\ C^2) \qquad (3)$$

où Q représente le rayonnement effectivement reçu, Q_A le rayonnement virtuel (valeur d'Angot), et C la nébulosité moyenne exprimée en dixièmes.

Le terme du second degré de cette équation était significatif à 0,1 % près alors que le terme du troisième degré, qui avait été également calculé, n'était pas significatif et a donc été omis.

Il convient de signaler ici qu'un certain nombre d'erreurs peuvent se glisser dans le calcul de l'équation (3) ci-dessus. Elles peuvent être groupées en plusieurs catégories :

1. Sources d'erreurs possibles sur les données Q :
   - *a*) Les valeurs moyennes mensuelles sont calculées dans chaque cas pour le nombre maximum d'années pour lesquelles on dispose de relevés, nombre qui varie d'un cas à l'autre.
   - *b*) Les relevés des diverses stations portent sur des périodes différentes, et toutes les stations ne continuent pas à faire de relevés.
   - *c*) Les stations ont utilisé des instruments de plusieurs modèles, dont la sensibilité ne concorde peut-être pas.
   - *d*) Il n'a pas été tenu compte des différences d'altitude des stations.
2. Sources d'erreurs possibles sur les données C :
   - *a*) Bien que les cartes de C soient fondées sur un grand nombre d'observations, elles sont généralisées et aplanies, si bien que la relation $\frac{Q}{Q_A}$: C risque d'être erronée pour une station donnée puisque les variations topographiques locales de C n'entrent pas en ligne de compte.
   - *b*) Des erreurs peuvent être commises par interpolation entre les lignes de niveau de C établis par Brooks.

En dépit des sources d'erreurs possibles, la relation semble être satisfaisante et elle est hautement significative à 0,1 % près. Ce qui a permis de la prendre comme base du calcul du rayonnement incident. Les valeurs de Q ont été déterminées aux intersections des méridiens et parallèles de 5 en 5 degrés sur les terres émergées et de 10 en 10 sur les mers. Ces valeurs ont été reportées sur une carte schématique où figurent les lignes de niveau du rayonnement incident. L'unité d'énergie utilisée est le rayonnement moyen quotidien, en calories reçues par centimètre carré d'une surface horizontale pour chaque mois. Il a été établi douze cartes de ce genre, une pour chaque mois.

Certaines caractéristiques de ces cartes pouvaient être prévues à l'avance : existence de zones de fort rayonnement aux environs de 20 à 30 degrés de latitude ; parallélisme des lignes de niveau dans l'hémisphère nord, par opposition à l'hémisphère sud où elles ont un tracé plus complexe ; rayonnement plus intense au-dessus des terres qu'au-dessus des mers à une même latitude, du fait d'une nébulosité moyenne supérieure au-dessus des mers ; présence de zones de faible rayonnement coïncidant avec la mousson d'été dans les pays qui la subissent ; tendance (en Australie par exemple) à la distinction entre deux zones de rayonnement maximum, par suite d'une nébulosité plus forte sur les chaînes montagneuses du centre. On peut rapprocher les données de ces cartes pour mettre en évidence le déplacement des zones de fort rayonnement durant l'année en simplifiant les cartes pour ne laisser subsister que les régions où le rayonnement est supérieur à 600 cal/cm²/jour et en les montant côte à côte ; la figure 1 illustre cette méthode. On constate naturellement que ces zones ont tendance à suivre le déplacement du soleil vers le nord et vers le sud, et qu'elles coïncident dans une très grande mesure avec les principales régions arides du monde.

Les recherches de l'Institut Wait sur le rayonnement solaire visaient à faire mieux connaître les conditions de végétations, notamment dans le domaine de l'évaporation et la physiologie des cultures ; nous espérons néanmoins que les cartes préparées à cet effet pourront rendre service à ceux qui s'occupent d'autres aspects du rayonnement solaire.

Un compte rendu détaillé des travaux esquissés ci-dessus, accompagné des cartes correspondantes, fera l'objet d'une autre publication.

LA DISTRIBUCIÓN DE LA RADIACIÓN SOLAR EN LA SUPERFICIE DE LA TIERRA

por

J.N. Black

Aunque en la actualidad se tiene cada vez más en cuenta la importancia de la radiación solar como factor ambiental, no sabemos todavía bastante acerca de la distribución de la radiación en la superficie del globo para poder estudiar bajo todos sus aspectos el papel que desempeña en el desarrollo de los sistemas de explotación del suelo aplicados en las diversas partes del mundo. De modo general, es difícil medir la radiación incidente ; en el curso de nuestras investigaciones, sólo pudimos reunir estadísticas sobre la radiación incidente sobre una superficie horizontal procedentes de ciento cincuenta estaciones meteorológicas. Además, la repartición geográfica de esas estaciones deja mucho que desear desde el punto de vista climatológico, ya que más del 70 % de ellas se encuentran en América del Norte o en Europa ; ninguna en América del Sur y sólo una de ellas en Asia. Resultaba evidentemente imposible trazar un mapa de la distribución de la radiación solar partiendo de los resultados de las observaciones directas, por lo que se ha considerado necesario proceder de otro modo.

Es sabido desde hace mucho tiempo que existe una relación entre la radiación recibida en la superficie de la tierra, y la duración de la insolación o, en otros términos, de la nubosidad media. La idea fué expuesta por primera vez por Angstrom [1][1], quien obtuvo el resultado siguiente para Estocolmo

$$Q = Q_0 \left(0{,}25 \times 0{,}75 \frac{n}{N}\right) \qquad (1)$$

donde Q representa la radiación efectivamente recibida ; Q_0 la radiación incidente con cielo despejado ; *n* la duración de la insolación eficaz y N la duración máxima posible de la insolación.

Esa ecuación y la ecuación correspondiente en la que la nubosidad media substituye la expresión $\frac{n}{N}$ han sido recientemente estudiadas en detalle por Berg [2] quien ha demostrado que esas relaciones dejan de ser perfectamente lineales en los casos de bajos valores $\frac{n}{N}$ o de valores elevados de la nubosidad (C), y por lo tanto conviene no utilizarlas sino para el cálculo de los valores medios mensuales.

El mismo principio se ha extendido [3] al examen de la relación entre Q, Q_A y $\frac{n}{N}$ en la que Q_A es el valor teórico de la radiación que se recibiría si la atmósfera fuera perfectamente transparente, partiendo de los valores de Angot [4]. Ese método ha permitido estudiar la distribución de la radiación incidente en todo el globo ya que, contrariamente a Q_0, los valores Q_A pueden obtenerse inmediatamente en todos los lugares del globo y en toda época del año. El análisis de los datos Q, Q_A y $\frac{n}{N}$ obtenidos por treinta y dos estaciones donde los doce valores mensuales de Q y de $\frac{n}{N}$ son conocidos, han permitido establecer la ecuación siguiente:

$$Q = Q_A \left(0{,}23 \times 0{,}48 \frac{n}{N}\right) \qquad (2)$$

Esa ecuación ha sido considerada generalmente aplicable en latitudes muy diversas, pero desgraciadamente ha resultado imposible utilizarla para determinar la distribución de la radiación solar en todo el globo, por no disponer de estadísticas completas en el tiempo y en espacio de la duración de la insolación máxima. Por consiguiente, se ha decidido estudiar la relación entre $\frac{Q}{Q_A}$ y la nubosidad (C), tomando para valores de C los que figuran en los mapas establecidos por C.E.P. Brooks en el segundo volumen del *Manual de Meteorología* de Napier Shaw [5]. De las ciento cincuenta estaciones de las que se dispone de datos sobre la cantidad de energía solar incidente, se ha comprobado que ochenta y ocho podían suministrar valores mensuales medios para períodos de más de tres años, y únicamente ésas han sido aceptadas. Los valores de C en esas estaciones han sido tomados de los mapas y se ha obtenido la ecuación siguiente por análisis de regresión:

$$Q = Q_A\ (0{,}803 - 0{,}340\ C - 0{,}458\ C^2) \qquad (3)$$

en la que Q representa la radiación efectivamente recibida ; Q_A la radiación virtual (valor de Angot) y C la nubosidad media expresada en décimas.

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[1] Las cifras entre corchetes remiten a la bibliografía adjunta al fin de este informe.

El término de segundo grado de esa ecuación era significativo a una aproximación de 0,1 %, mientras que el término del tercer grado, que había sido igualmente calculado, no era significativo y por lo tanto ha quedado omitido.

Conviene aquí señalar que pueden introducirse cierto número de errores en el cálculo de la ecuación (3) antes citada. Esos errores pueden agruparse en varias categorías:

1. Fuentes de errores posibles sobre los datos Q:
   a) Los valores medios mensuales son calculados en cada estación para el número máximo de años sobre los que se dispone de información, número que varía de un caso a otro.
   b) Las indicaciones de las diferentes estaciones no se refieren todas al mismo período de tiempo, y no todas las estaciones llevan un registro de esas indicaciones.
   c) No todas las estaciones han utilizado los mismos instrumentos, y es posible que la sensibilidad de éstos sea diferente en los distintos casos.
   d) No se han tenido cuenta de las diferencias de altura de las estaciones.
2. Fuentes de errores posibles sobre los datos C:
   a) Aunque los mapas de C hayan sido preparados basándose en un gran número de observaciones, las curvas han sido extrapoladas y aplanadas. La relación $\frac{Q}{Q_A}$: C corre el riesgo de ser errónea en el caso de determinadas estaciones por no haberse tenido en cuenta las variaciones topográficas locales de C.
   b) Pueden haberse cometido errores por interpolación entre las isopletas de C establecidas por Brooks.

A pesar de esas fuentes de errores posibles, la relación parece satisfactoria y es altamente significativa a una aproximación de 0,1 %. Por ese motivo se han tomado como base del cálculo de la radiación incidente, y los valores de Q han sido determinados en las intersecciones de los meridianos y paralelos de 5 en 5 grados sobre las tierras y de 10 en 10 grados sobre los mares. Esos valores han sido marcados sobre un mapa esquemático en el que han sido trazadas las isopletas de la radiación incidente. La unidad de energía utilizada es la radiación media cotidiana, en calorías recibidas por centímetro cuadrado de una superficie horizontal para cada mes. Se han preparado dore mapas de ese tipo, uno para cada mes.

Algunas características de esos mapas no son sorprendentes: aparición de zonas de gran radiación a unos 20 o 30 grados de latitud ; paralelismo de las isopletas en el hemisferio norte por oposición al hemisferio sur donde tienen un trazado más complejo ; radiación más intensa sobre las tierras que sobre los mares en una misma latitud, debido a que la nubosidad media es más fuerte sobre las superficies de agua ; presencia de zonas de débil radiación que coinciden en todas partes con el monzón de verano y en algunos territorios como Australia por ejemplo, presencia de dos zonas de radiación máxima resultante de una nubosidad más fuerte sobre el sistema orográfico central. Al comparar los datos ofrecidos por esos mapas, es posible hacer resaltar el desplazamiento de las zonas de fuerte radiación durante el año entero simplificando los mapas de modo que no indiquen más que las regiones donde la radiación es superior a 600 calorías por centímetro cuadrado y por día y, montándolos uno al lado de otro ; la figura 1 ilustra este método. Como se esperaba, esas zonas tienden a seguir el desplazamiento del sol hacia el norte y hacia el sur y coinciden en gran medida con las principales regiones áridas del mundo.

Los trabajos efectuados en el Instituto Waite sobre la radiación solar tenían por objeto un mejor conocimiento del medio vegetal, sobre todo en lo que se refiere a la evaporación y a la fitofisiología de los cultivos ; esperemos que estos mapas sean de utilidad a las personas que se ocupan de otros aspectos de la radiación solar.

Se encuentra en prensa un informe detallado de los trabajos mencionados en el presente estudio, junto con los mapas a que se hace referencia.

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SOLAR AND SKY RADIATION IN SOUTHERN AFRICA

by

A. E. H. BLEKSLEY

INTRODUCTION

At the mean distance of the earth from the sun, the intensity of solar radiation amounts to very nearly 2 calories per minute on each square centimetre of surface normal to the incident radiation. In the passage of the sunlight through the earth's atmosphere to the surface, a considerable proportion of this energy is, however, lost for the purposes of utilization of the energy, and it is a matter of importance to determine, by observations over as large a portion of the surface as possible, so as to cover all possible climatic zones, the amount of radiation available at the surface at various times.

In its passage through the atmosphere, the radiation losses in the direct beam occur as the result of the following processes: (a) absorption by the gases and vapours of the atmosphere, principally in the infra-red water-vapour bands; (b) scattering of the light back into space by the molecules and dust particles in the air; (c) scattering of light towards the ground by the molecules and dust particles in the air. This loss from the direct solar beam gives rise to the sky radiation, which can, under suitable circumstances, be used to compensate at least partly for the direct radiation loss.

Measurements of the direct solar radiation and of the scattered sky radiation have been carried out in various parts of the world over the last forty years or more. These observations have, however, in the majority of cases referred to climatic regions which differ very greatly from the arid zones in which, for the purposes of this symposium, we are particularly interested. During the past few years, nevertheless, a great deal of material regarding the intensity of solar and sky radiation in southern Africa has been collected, mainly through the activity of the radiation section of the South African Weather Bureau and is now available. It is the purpose of this paper to discuss it, with special reference to the problem of solar energy utilization in this region. Much of this material has not previously been published, and I am greatly indebted to Dr. T. E. W. Schumann, Director of the Weather Bureau, and to Mr. A. J. Drummond, the officer in charge of the solar radiation section, for making it available to me.

SMITHSONIAN INSTITUTION ASTROPHYSICAL OBSERVATORY OBSERVATIONS OF SOLAR ENERGY

Probably the most prolonged series of observations of the normal intensity of the direct solar beam has been carried out, over a period of many years, by the Astrophysical Observatory of the Smithsonian Institution of Washington. In the course of the study of the solar constant and its variation which has occupied that institution largely for thirty years or more, observations by means of standardized pyrheliometers have been carried out at field stations in various of the most arid regions of the world, and the results constitute a mass of information of great value.

In 1926, after investigating the suitability of sites in Algeria, Egypt and Baluchistan, it was decided to erect a station at Mount Brukkaros in South West Africa (Long. 17° 48′ E., Lat. 25° 52′ S.). Brukkaros is an isolated explosion crater 5,000 ft. (1,525 m.) in elevation, rising precipitously from a level plateau of 3,000 ft. (915 m.) elevation. The average yearly rainfall in the vicinity is approximately 90 mm., of which about two-thirds occurs during February and March, which are also the cloudiest months. The observations showed that the skies in that region are extraordinarily clear.

The station was maintained on Brukkaros for about five and a half years, and was finally abandoned because it had become clear that for the determination of the solar constant the presence over long periods of a very high layer of dust from the Kalahari Desert was a disturbing factor. The pyrheliometer observations taken during that period, however, constitute the longest series of such measurements yet made in southern Africa.

These observations have not been published *in extenso;* only the daily solar constant determinations. Through the courtesy of the director of the Astrophysical Observatory, however, the detailed pyrheliometric results have recently been made available to Mr. A. J. Drummond of the Weather Bureau, and are to be published shortly, along with much additional material, in the *Archiv für Meteorologie, Geophysik und Bioklimatologie* (Vienna).

For the purposes of the present discussion, these pyrheliometric observations of the normal intensity of the direct solar beam (the final values reduced from the Smithsonian pyrheliometry to the Angstrom scale by the relation recommended by the World Meteorological Organization, viz., Smithsonian/Angstrom = 1.035) are summarized in Table 1, where we give the mean annual values of intensity of solar radiation at Brukkaros in cal./cm.^{2}/min.$^{-1}$ for various values of the altitude of the sun, and also for various values of the absolute air mass. These observations, owing to the demands of the solar constant programme, were carried out on cloudless days for which, in addition, the sky was very clear, i.e. largely free from dust.

TABLE 1. Mean annual values of intensity of solar radiation at Brukkaros (cal./cm.^{2}/min.)

Solar altitude	*Radiation*	*Solar altitude*	*Radiation*	*Solar altitude*	*Radiation*
85°	1.530	60°	1.497	35°	1.379
80°	1.529	55°	1.482	30°	1.339
75°	1.524	50°	1.461	20°	1.226
70°	1.518	45°	1.440	10°	0.971
65°	1.509	40°	1.412		

Air mass	*Radiation*	*Air mass*	*Radiation*	*Air mass*	*Radiation*
0.75	1.562	2.25	1.247	3.50	1.086
1.00	1.485	2.50	1.212	3.75	1.059
1.25	1.420	2.75	1.178	4.00	1.033
1.50	1.367	3.00	1.147	4.25	1.008
1.75	1.322	3.25	1.116	4.50	0.985
2.00	1.283				

RADIATION ON VARIOUS SURFACES AT BRUKKAROS

From Table 1 it is possible to compute, for conditions of cloudless sky, the average total daily radiation for each month of the year. In Table 2 we give for each month the mean daily radiation obtained in this way for the following surfaces: (a) a movable surface always normal to the incident radiation (I_N); (b) a vertical surface rotated so that its normal is always in the vertical plane through the incident beam (I_V); and (c) a (fixed) horizontal surface (I_H).

TABLE 2. Mean daily radiation (cal./cm.^{2}) incident on given surface, for cloudless sky conditions at Brukkaros

Month	I_N	I_V	I_H
Jan.	1,066	652	729
Feb.	1,017	651	682
Mar.	944	665	597
Apr.	860	670	489
May	788	660	392
June	743	640	343
July	759	652	363
Aug.	829	664	445
Sept.	915	671	556
Oct.	984	643	650
Nov.	1,048	641	713
Dec.	1,081	654	741
Mean.	920	655	558

The table shows clearly that the variation in the vertical component (I_V) from month to month is very small; this arises from the fact that during the summer the sun is higher at noon, so that its radiation on a vertical plane is less than during a corresponding period in the winter yet, owing to the greater length of the summer day (some three and a half hours longer than in winter), the morning and afternoon contributions almost exactly counteract this differential effect. The radiation on a horizontal plane (I_H) is subject, however, to very considerable variation, while its mean is a great deal lower than that of I_V.

However, the practical utilization of either I_N or I_V necessitates the use of movable collecting surfaces, with the attendant practical and economic difficulties, while the use of I_H involves only a fixed horizontal collecting surface. It is therefore worth computing, in the same way, the radiation incident on certain other plane surfaces, such as may in practice be considered for the collection of the incident energy; and these further calculations are summed up in Table 3. The surfaces considered here are inclined to the horizontal, as in a pitched roof, the normal being directed towards the meridian, and the inclination to the horizontal being respectively equal to the latitude (i.e. the surface is parallel to the earth's axis), the latitude plus 5°, and the latitude plus 10°. The tilt, in the case of a collector surface in the southern hemisphere, is towards the north.

From this table it is clear that the average I_P during the year is not greatly dependent on the inclination of the collector plane to the horizontal. Since, however,

TABLE 3. Mean daily radiation (cal/cm²) on fixed plane surfaces at angle i to horizon, for cloudless sky at Bloemfontein

Period	I_L i = Lat.	i = Lat. + 10°	i = Lat. + 20°
Dec.–Jan.	[illegible]	[illegible]	[illegible]
June–July	[illegible]	[illegible]	[illegible]
Mar.–Apr. Sept.–Oct.	[illegible]	[illegible]	[illegible]
Average	[illegible]	[illegible]	[illegible]

the normal intensity is less in winter than in summer, an inclination about 10° greater than the latitude—which provides more favourable collecting conditions during the winter—gives, as is clear from the last column, a more even distribution of intensity. By comparison with Table 3, we see that the mean I_L lies approximately midway between the means of I_v and I_c; it is more uniformly distributed over the year than I_c and a good deal easier to obtain in practice than I_v. The most suitable collector surface for small scale applications of solar energy would therefore appear to be a surface tilted towards the sun at an inclination about 10° greater than the latitude.

On the other hand, for industrial purposes, where the expense of a movable collector might be justified, as in the generation of very high temperatures, it is clear that a collector surface normal to the incident radiation is the most efficient. Such a collector surface is capable of being driven at the required speed by a simple synchronous motor drive, whereas the drive needed to enable a tilted surface to follow the sun is a good deal more complicated.

The foregoing calculations have referred entirely to direct solar radiation on cloudless days. In practice, however clear the sky, there is also a certain amount of scattered sunlight from the sky itself, so that to all the foregoing quantities a (largely unknown) amount of energy due to this sky radiation must be added. In certain cases there may also be considered an additional contribution due to radiation reflected from the surrounding terrain. Very little information is as yet available regarding this last factor, but we shall now proceed to consider the magnitude of the sky radiation on a horizontal surface, from observations carried out by the South African Weather Bureau at Windhoek, South West Africa (Long. 17° 06′ E.; Lat. 22° 34′ S.; elevation 5,600 ft. (1,700 m.)).

TOTAL AND DIFFUSE RADIATION AT WINDHOEK

In October 1956 a radiation section was established in the Union's Weather Bureau, for the purpose of providing a long-term homogeneous record of the solar radiation reaching the earth's surface. At the headquarters of the bureau in Pretoria a central control has been set up, containing fundamental pyrheliometers of the Ångström electrical compensation type which have been carefully standardized and serve to standardize all secondary instruments. The Ångström scale has been independently established, from fundamental principles, with an accuracy of ±0.3 per cent, and secondary standards can be calibrated to within ±1 per cent.

At a number of stations throughout the Union and South West Africa continuous records of the total and the diffuse sky radiation falling on a horizontal plane are now obtained by means of standardized Kipp thermoelectric solarimeters, coupled to self-registering microammeters. Among the stations so far established, that at Windhoek, which has operated since July 1957, has the closest relationship to the problems of the arid zones, and its results have therefore been chosen for consideration in the present paper.

The average rainfall at Windhoek is approximately 350 mm. per annum, mostly between November and February (summer rains). In many respects, particularly latitude, altitude and clarity of atmosphere, conditions at Windhoek are not greatly divergent from those at Bloemfontein.

In Table 4 we give the mean daily sums of total radiation (T) and diffuse radiation (D) on a horizontal plane for each month at Windhoek, for cloudless days (which are thus comparable with the Bloemfontein observations), and for all days. The results are given, as usual, in cal/cm².

TABLE 4. Mean daily sums of total (T) and diffuse (D) radiation at Windhoek (cal/cm²)

Month	Cloudless days T	Cloudless days D	All days T	All days D
Jan.	[illegible]	[illegible]	[illegible]	[illegible]
Feb.	[illegible]	[illegible]	[illegible]	[illegible]
Mar.	[illegible]	[illegible]	[illegible]	[illegible]
Apr.	[illegible]	[illegible]	[illegible]	[illegible]
May	[illegible]	[illegible]	[illegible]	[illegible]
June	[illegible]	[illegible]	[illegible]	[illegible]
July	[illegible]	[illegible]	[illegible]	[illegible]
Aug.	[illegible]	[illegible]	[illegible]	[illegible]
Sept.	[illegible]	[illegible]	[illegible]	[illegible]
Oct.	[illegible]	[illegible]	[illegible]	[illegible]
Nov.	[illegible]	[illegible]	[illegible]	[illegible]
Dec.	[illegible]	[illegible]	[illegible]	[illegible]
Mean	[illegible]	[illegible]	[illegible]	[illegible]

From this table it is clear that even on cloudless days in this region of clear skies, the diffuse radiation from the sky amounts on the average to more than 10 per cent of the direct solar radiation, while on cloudy days the diffuse radiation can become very large indeed. The presence of a certain amount of cloud, even possibly obscuring the sun, must not be taken

of solar energy we require low values under (a) and (b).

TABLE 6. Percentage frequency distribution of sunshine

Station	*(a)*	*(b)*	*(c)*	*(d)*	*(e)*
Armoedsvlakte	1.3	3.5	11.5	40.4	43.5
Beaufort West	1.2	3.1	8.7	44.5	42.5
Bloemfontein	1.5	3.5	8.3	37.6	49.2
Kimberley	0.6	2.4	10.2	36.5	50.5
Potchefstroom	1.1	3.4	12.6	42.0	40.7
Pretoria	1.9	4.6	11.3	38.0	44.4

From these representative results it seems clear that in the greater part of the interior a succession of two or more completely cloudy days must be a relatively rare phenomenon. On the whole, on not much more than 5 per cent of all days during the year will the sunshine probably amount to less than 10 per cent of the maximum, while on about half the days of the year it will exceed 90 per cent of the possible. Since in this region the greater part of the rainfall, and hence also of dense cloud, is in the summer, it appears clear that solar energy should prove very satisfactory for the heating of homes during the colder months.

INFLUENCE OF AMBIENT AIR TEMPERATURES

For some time to come the utilization of solar energy probably will be limited to relatively small scale applications, such as domestic heating, hot water supply, and as a heat source for absorption-type refrigeration units. For such applications the energy is required at moderate temperatures, generally not exceeding 100° C.; in which case the solar radiation can be collected directly, i.e. without the use of concentrating devices such as reflecting mirrors. The collector will therefore generally be of the "flat plate" type, probably mounted, as suggested in the section on radiation on various surfaces at Brukkaros, at an inclination to the horizontal equal to approximately the latitude + 10°.

The collector, painted black to absorb the radiation, is insulated from the air on the reverse side to cut down heat losses; for the same purpose on the front side there must be one or more air-spaced glass plates through which the sunlight passes. Without entering into the design problems involved, we can at this stage mention the fact that the rate at which energy can be removed from the collector depends in the main on two factors: the flux of incoming radiation, and the rate at which heat is being lost to the ambient air. This latter factor is determined by the temperature level of collection (which depends mainly on the purpose for which the energy is to be used), and also on the temperature of the air. Hence the average daytime air temperature is a geophysical factor of some importance. The warmer the air, the greater the collecting rate for a given collecting temperature.

A great deal of meteorological information relating to air temperatures is, of course, available, and there is little point in giving much information of this kind here. As one example, however, of the situation in the arid parts of southern Africa, we give in Table 7 the mean monthly values of air temperature during the day over the period 6 a.m. to 6 p.m. for Keetmanshoop in South West Africa. Keetmanshoop is approximately 60 miles from Brukkaros, and is subject to similar climatic conditions. These figures can therefore be taken in conjunction with the solar radiation figures previously given for Brukkaros.

TABLE 7. Monthly mean values of daytime air temperatures at Keetmanshoop

Month	*Mean temp °C.*	*Month*	*Mean temp °C.*
Jan.	27.9	Jul.	15.4
Feb.	28.7	Aug.	17.7
Mar.	26.0	Sept.	21.3
Apr.	23.8	Oct.	23.4
May	19.4	Nov.	27.3
June	16.5	Dec.	30.0

During the summer, therefore, heat could be collected at the same rate from an inclined collector plate at a temperature around 15° C. higher than would be possible during the winter.

CONCLUSION

Although the observations of the available solar energy discussed in the foregoing have referred in the main to two stations only, the general trend of the observations would probably also be reflected in a very large part of the more arid regions of southern Africa. It should also be noted that the climate of these regions is by no means unique. In fact all countries situated within the high pressure belts of both hemispheres show similar characteristics.

Thus in the southern hemisphere the Argentine and Australia, and in the northern hemisphere the southwestern United States, northwestern Mexico, northern Africa, Arabia and the Mediterranean countries show similar sunshine values. A factor of possible importance in improving conditions in southern Africa above those prevalent in these other regions is the comparatively high altitude of a great part of the interior, but this is unlikely to affect seriously the general trend of our conclusions.

In conclusion, it may be said that over large areas of the globe the incidence and intensity of the solar radiation, direct and diffuse, are such as to render the application of solar energy, at least on a small scale, eminently practicable.

RAYONNEMENT SOLAIRE DIRECT ET DIFFUS EN AFRIQUE MÉRIDIONALE

par

A. E. H. BLEKSLEY

RÉSUMÉ

La plus grande partie de la région aride de l'Afrique méridionale est subtropicale ; elle se trouve à une altitude moyenne d'environ 1.200 mètres et présente en gros les caractéristiques climatiques suivantes : *a*) faible pluviosité — les précipitations ont surtout lieu durant les mois d'été ; *b*) faible nébulosité ; *c*) ciels d'une grande transparence ; *d*) rayonnement solaire de forte intensité.

Ces caractéristiques ne sont pas particulières à cette région ; elles se retrouvent dans toutes celles qui sont situées dans les zones de hautes pressions de l'un ou l'autre hémisphère. L'étude de l'intensité du rayonnement solaire et céleste en Afrique du Sud peut donc servir à résoudre les problèmes plus vastes que pose l'utilisation de l'énergie solaire dans les régions arides d'autres parties du monde.

Les données les plus détaillées dont nous disposons actuellement proviennent d'un programme d'étude des radiations récemment mis en application par l'Office météorologique de l'Union Sud-Africaine. Il existe cependant une abondante série d'observations sur l'intensité du rayonnement solaire direct, effectuées entre 1926 et 1931 au mont Brukkaros, dans le sud-ouest africain par l'observatoire d'astrophysique de la Smithsonian Institution de Washington. Les résultats détaillés de ces travaux n'ont pas encore été publiés ; nous devons à l'amabilité du directeur de cet observatoire d'en avoir eu connaissance.

D'après les observations pyrhéliométriques faites au mont Brukkaros, nous avons calculé les valeurs annuelles moyennes de l'intensité du rayonnement solaire à Brukkaros pour différentes hauteurs du soleil (tableau 1) et avons déduit des valeurs obtenues le rayonnement quotidien moyen pour un ciel sans nuages, sur les collecteurs suivants : *a*) une surface mobile constamment maintenue dans un plan perpendiculaire au rayonnement incident ; *b*) une surface verticale animée d'un mouvement de rotation tel que sa normale soit constamment dans le plan vertical du rayonnement incident ; *c*) une surface horizontale (fixe) ; *d*) une surface dont l'inclinaison par rapport à l'horizontale est égale à la latitude et dont la normale est dirigée vers le méridien à son point d'intersection avec l'Équateur céleste ; *e*) une surface analogue dont l'inclinaison est égale à la latitude augmentée de 5 degrés ; *f*) une surface analogue dont l'inclinaison est égale à la latitude augmentée de 10 degrés.

Les résultats obtenus dans les trois premiers cas sont donnés dans le tableau 2 et ceux qui correspondent aux trois dernières surfaces dans le tableau 3.

Ces tableaux montrent que le meilleur collecteur mobile est celui du type *a*), c'est-à-dire un plan perpendiculaire au rayonnement incident, alors que le meilleur collecteur fixe est du type *f*) ; ce qui conduirait à situer les surfaces réceptrices sur le versant nord du toit des maisons si l'on veut faire servir l'énergie solaire à des usages domestiques.

Ces calculs valent pour le rayonnement solaire direct par temps clair. En réalité, si dégagé que soit le ciel, il y a toujours une certaine proportion de rayonnement céleste (diffus), dont l'intensité a été étudiée d'après des observations faites à Windhoek au moyen de solarimètres thermoélectriques normalisés de Kipp, équipés d'un dispositif d'enregistrement. Ces observations, résumées dans le tableau 4, montrent que même par temps clair le rayonnement diffus reçu sur un plan horizontal équivaut généralement à plus de 10 % du rayonnement direct. La nébulosité peut augmenter

considérablement ce pourcentage. La présence d'une certaine quantité de nuages, même s'ils cachent le soleil, ne doit donc pas être considérée comme supprimant complètement tout rayonnement incident sur un plan collecteur horizontal. Il semble bien que, sauf lorsque le ciel est complètement bouché, la présence d'un rayonnement diffus compense largement la déperdition de rayonnement direct due aux nuages ou à l'abondance de poussières dans l'atmosphère.

Les observations dont il a été question plus haut, n'ayant été faites que dans deux stations, il a fallu les compléter par des données statistiques sur l'ensoleillement et la nébulosité en Afrique du Sud, rassemblées au moyen d'appareils enregistreurs Campbell-Stokes et récemment publiées par l'Office météorologique. Ces statistiques, reproduites dans les tableaux 5 et 6, montrent que dans la région qui nous occupe la moyenne annuelle des heures de plein soleil représente 80 % du maximum possible. Compte tenu du fait que le rayonnement diffus entre pour une grande part dans l'énergie fournie par le rayonnement solaire direct, il semble bien que sur une fraction considérable du territoire sud-africain, il serait possible de capter 80 à 90 % du plus grand rayonnement possible. Les applications possibles de l'énergie solaire au chauffage domestique durant la saison froide sont favorisées du fait que le total des heures ensoleillées ne diminue guère pendant les mois d'hiver. La distribution des jours ensoleillés dans l'année (tableau 6) montre qu'il n'y a guère plus de 5 % des jours de l'année où l'ensoleillement soit inférieur au dixième du maximum possible, alors qu'il dépasse les neuf dixièmes de ce maximum pendant près de la moitié des jours de l'année.

L'auteur traite enfin de la température de l'air ambiant durant la journée et aboutit à cette conclusion que, dans les pays ayant les mêmes caractéristiques climatiques que l'intérieur du territoire sud-africain, la durée et l'intensité du rayonnement solaire direct et diffus sont telles que l'utilisation de l'énergie solaire, du moins à petite échelle, est parfaitement possible.

LA RADIACIÓN SOLAR Y CELESTE EN ÁFRICA DEL SUR

por

A. E. H. Bleksley

RESUMEN

La mayor parte de la zona árida del África meridional es una región subtropical que tiene una altitud media de unos 1.200 metros y presenta en general las siguientes características climatológicas: *a*) escasa precipitación pluvial, concentrada principalmente en los meses estivales; *b*) escasa nubosidad; *c*) cielos de alta transparencia; *d*) radiación solar de alta intensidad.

Esas condiciones no son excepcionales, pues se encuentran en todas las regiones situadas en las zonas de alta presión atmosférica de ambos hemisferios. Por ello, la investigación de la intensidad de la radiación solar y celeste en África del Sur puede ser de interés para la solución del problema general de la utilización de la energía solar en las regiones áridas de todo el mundo.

Los datos más detallados que hoy poseemos son resultado del programa de investigaciones sobre la radiación solar establecido por la Oficina Meteorológica de la Unión Sudafricana. Por otra parte, también disponemos de una larga serie de observaciones sobre la intensidad de la radiación solar directa llevada a cabo en Mount Brukkaros, África Sudoccidental, entre 1926 y 1931 por el observatorio astrofísico allí establecido por la Smithsonian Institution de Wáshington.

A base de las observaciones piroheliométricas realizadas en Brukkaros, hemos calculado los valores medios anuales de la intensidad de la radiación solar en Brukkaros a distintas altitudes del sol (tabla 1). De esos valores hemos deducido la radiación diaria media de cielos despejados recogida de las siguientes superficies: *a*) una superficie móvil normal a la radiación incidente; *b*) una superficie vertical dotada de una rotación tal que su plano normal coincida con el plano vertical en el que se inscribe el rayo incidente; *c*) una superficie horizontal fija; *d*) una superficie orientada hacia el ecuador e inclinada de manera que forme un ángulo con la horizontal igual al valor

de la latitud, en su situación geográfica el plano normal de dicha superficie coincide con el plano del meridiano; *e*) una superficie determinada como la anterior pero cuyo ángulo con la horizontal es igual a la latitud más cinco grados; *f*) una superficie determinada como las anteriores pero cuyo ángulo con la horizontal es igual a la latitud más 10 grados.

Los resultados de los tres primeros casos se hallan recogidos en la tabla 2; los de los tres últimos en la tabla 3.

Esas tablas muestran que la superficie colectora móvil más eficaz es la de tipo *a*, es decir la normal, y la fija la de tipo *f*; ello implica que es preferible usar superficies colectoras de la energía solar para su utilización doméstica en los techos inclinados de orientación norte.

Los cálculos se refieren a la radiación solar directa en días despejados. Sin embargo, en la práctica, por muy despejado que esté el cielo siempre existe una cierta radiación celeste (difusa) cuya magnitud se expresa en términos de las observaciones realizadas en Windhoek con solarímetros termoeléctricos Kipp estandarizados y dotados de un registro eléctrico. Tales observaciones, resumidas en la tabla 4, muestran que, aun en los días de cielo despejado, la magnitud de la radiación difusa que incide sobre un plano horizontal excede generalmente el 10 % de la radiación directa. Cuando hay nubes, este porcentaje crece considerablemente. Por consiguiente, la presencia de nubes, aun cuando estas obscurecan el sol, no significa la total desaparición de la radiación incidente sobre una superficie colectora horizontal. Resulta evidente por lo tanto que, excepto en los casos cuando el cielo está completamente encapotado, la presencia de la radiación difusa compensa considerablemente la pérdida de la radiación directa debida a las nubes o a grandes cantidades de polvo en la atmósfera.

Como las observaciones aquí resumidas se refieren únicamente a dos estaciones meteorológicas, estos datos pueden extenderse incluyendo los obtenidos sobre la duración de los períodos de insolación y sobre la nubosidad en Sudáfrica, tomados mediante los registradores de insolación de Campbell-Stokes y recientemente publicados por la Oficina Meteorológica. Dichas estadísticas recogidas en las tablas 5 y 6 muestran que, en la región estudiada, la duración anual media de la insolación alcanza el 80 % del máximo posible. Si se tiene en cuenta la importante contribución que aporta la radiación difusa a la energía recibida de los rayos solares directos, resulta evidente que en una proporción muy importante del interior del África del Sur sería posible recoger entre el 80 % y el 90 % de la radiación máxima posible. También tiene interés señalar, en vista de la posible aplicación de la energía solar a la calefacción doméstica durante los meses fríos, que no se observa una reducción apreciable del total de horas de insolación durante el invierno, época en que más necesario es el suministro de energía. La distribución de frecuencias de la tabla 6 indica que sólo en muy poco más del 5 % de los días del año, la duración de la insolación es inferior al 10 % del máximo posible, mientras que en la mitad de los días dicha duración excede las 9/10 del máximo posible.

También se indican las temperaturas ambientes durante el día, concluyéndose finalmente que en los países con características climatológicas semejantes a las del interior del África del Sur, la incidencia e intensidad de la radiación solar, tanto directa como difusa, hacen posible la aplicación —aunque sólo sea en pequeña escala— de la energía solar.

DISCUSSION

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Professor **Dresden**. I should like to state that the very complete statistical analysis by Dr. Bleksley for sunshine makes me, as a wind-power man, somewhat jealous. Of course Dr. Bleksley had the good fortune to have available a series of observations over five and a half years and so we shall have to show some patience in collecting similar data for the wind. This does not mean, however, that we should wait for these results before installing plants in suitable places; it simply means that we may hope to be able to choose with even more certainty as the necessary statistics become available. Maybe the jealousy gives an extra stimulus to our work in this field.

SOLAR RADIATION: EXPERIENCE, POSSIBILITIES AND PROSPECTS OF ITS EXPLOITATION

by

Professor V. A. BAUM

INTRODUCTION

Nearly all the several kinds of energy we use for our material and cultural needs are, in the final instance, results of the activity of the sun's rays. The mechanical energy of falling water or of wind, the chemical energy of coal, peat or wood, the muscular energy of animals or of man himself, are all of them solar radiation energy which has undergone a number of transmutations proceeding in nature on a vast scale.

Today, energy is produced chiefly by burning mineral fuel, about 80 per cent of the world's total power output coming from this source. This can hardly, however, last very long, as under present conditions of consumption the fuel supplies may be exhausted in the none too distant future. This has again and again been pointed out by economists of various countries who have estimated the time—greatly varying, to be sure—when the "underground fuel stores" would give out.

Though not arousing anxiety for the near future this, however, calls attention to the necessity of tapping other sources of energy, particularly the so-called eternal sources: solar radiation and its derivatives—wind and falling water.

The sources of energy are quite unevenly distributed on the earth's surface, and in different regions each of them may have advantages over the others. Vast expanses of our globe are occupied by subtropical and intracontinental arid zones. Thanks to certain conditions of atmospheric circulation, the sky in these regions is stably cloudless the greater part of the year and the sun sends down vast amounts of energy upon the surface of the earth.

In such districts it may be advantageous to meet certain of the population's power needs by harnessing solar radiation, especially when it is the only source of energy. Mastery and extensive dissemination of methods of converting the radiant energy of the sun into other kinds of energy required for domestic and industrial purposes would greatly facilitate the development of these districts and the improvement of the conditions of life.

Wider employment of solar installations in arid zones will make for fuller utilization of the sun's radiation and will improve the heat balance of the earth. In the future, attention will undoubtedly be devoted to the possibility and the profitability of such interference by man in the spontaneously proceeding processes of solar radiation transformation—making it possible to change the climate of some regions, arranging it rationally by properly distributing the exploitation of solar energy and altering the thermophysical and radiation conditions of these regions.

Deserts should be returned to life by the same forces of nature which, gradually advancing upon flourishing land, dried, parched and made it barren. Man is able to compel the sun to perform this cosmically vast job. Many scientists, engineers and practical workers of different countries and nationalities, of modern and past times, have prepared the ground for tackling these problems.

PRESENT STATE OF RESEARCH ON SOLAR ENERGY

In the Soviet Union, arid zones occupy some 3 million km.^{2}, of which over 800,000 km.^{2} are sand deserts. These zones have up to 150-200 clear sunny days a year; horizontal surfaces here get more than a million kg. calories of solar energy per m.^{2} a year; surfaces rotating in the direction of the apparent movement of the sun receive up to 2 million kg. calories per m.^{2} a year.

Economic considerations determine first of all the expediency of exploiting solar energy. Radiant energy can be converted into other kinds of energy directly or through a number of consecutive transformations. All solar installations in practical use operate on the principle of the conversion of the sun's radiant energy into heat which is used by consumers direct or is subjected further to required transformations. Other methods, though technically feasible, are bulky or intricate and, in the final instance, unsuitable.

Thermoelements can now convert into electrical energy about 6 per cent of the heat flowing through them. This is a much smaller efficiency than can be obtained through solar heat and power plants (up to 15 per cent). The use of thermoelements does not essentially simplify solar installations: the temperature of the hot couples of the thermopile must be about 500° C. Solar thermoelectric generators must therefore have revolving mirrors, and that is the most expensive part of the solar outfits. It may be concluded that thermoelectric generators are less effective in solar than in fuel installations.

Photo cells as yet have a low efficiency and are too expensive to compete with the outfits mentioned. The methods of converting radiant energy through artificial photosynthesis are still in the stage of laboratory experimentation.

Photosynthesis, which is widely effected in nature by green plants, requires fertile soil. Moreover, from the energy point of view, it is not economical: it utilizes 1.5 to 3 per cent of the solar energy; hence to grow plants for the purpose of burning them to obtain energy is not rational.

The conclusions given here are based on existing facilities for the practical use of the processes and apparatuses under review. Improvements in the physical processes, in their technical application etc., may call for different recommendations.

Solar energy can be used for various purposes and on a varied scale, which in each given case should be determined by careful calculations based on both theory and experiment.

The tasks with a view to theoretical, experimental and practical use of solar energy may be divided into the following five groups: (a) study of the radiation and heat balance of the earth and its definite regions; (b) elaboration of questions of the rational distribution and utilization of this energy; (c) elaboration of methods of converting solar energy; (d) development of apparatuses for the exploitation of solar energy; (e) elaboration of schemes for the integrated utilization of solar energy for different purposes.

SOLAR ENERGY RESEARCH IN THE U.S.S.R.

Our institute has, over a number of years, been conducting and co-ordinating the work of studying the solar climate; of creating new and improving existing solar installations; of experimenting with them; of working out calculation methods; of ascertaining the possible spheres of practical application of these installations.

Below we give the results or conclusions of our investigations, dealing mainly with practical questions.

Installations for the exploitation of solar radiation may be divided into two groups: (a) without concentrators of solar rays; (b) with concentrators.

When heating to moderate temperatures is required, apparatuses without concentrators are used—plane collectors which have been worked out in sufficient detail in diverse variants and for various purposes.

This sun heater is a shallow box with well insulated walls and bottom. On the top it is covered with one or two plates of glass with an air space of 2-3 cm. between them.

Rotation of the plane collectors following the route of the apparent movement of the sun would increase their capacity, but it would also increase their cost. Therefore they are usually set in a fixed position on the ground, or on the roof of a building, with their angle of slope in relation to the horizontal surface equalling the geographic latitude of the given locality, and their glassed surface facing south. Their operation is based on the principle that the stream of radiant energy coming through the glass plate, and losing about 10 per cent of its intensity as it passes through each glass, reaches the blackened bottom of the collector. Part of the energy that reaches the bottom is radiated back into space (about 10-15 per cent). The remainder is absorbed and transformed into heat which, except a certain portion emitted through the walls, bottom and glass, can be put to use.

In this manner are built water heaters, vegetable and fruit driers, air heaters and other moderate temperature apparatuses.

The use of plane collectors is restricted by the fact that they cannot produce high temperatures owing to the greatly increasing heat losses from their heated surfaces which are necessarily large.

To obtain temperatures above 100° C. the rays of the sun must be concentrated, which is achieved through glass or metal mirrors.

The area of the solar receiver's surface through which the radiation is absorbed is, approximately, inversely proportional to the concentration of the rays. Therefore, leaving details aside, it may be concluded that the heat losses by these surfaces are likewise inversely proportional to the concentration of the rays.

Solar installations with mirrors of greater concentration can therefore work also in the winter, on sunny days, with their efficiency practically not depending upon the temperature of the surrounding air. This widens the range of their use.

Such installations may be used for obtaining temperatures from 100° C. to—with precision mirrors—3,000° C. and higher. They can be used to boil water; to produce steam for technological purposes and high pressure steam; to heat and melt metals; to bake ceramics. Of the various forms of mirrors it is best to use parabolic-cylinder or paraboloidal ones. Depending on their precision, the parabolic-cylinder mirrors can increase the concentration of the sun's rays 20-70-fold, and the paraboloidal ones 300-5,000-fold and more.

The mirror installations must be so rotated that the rays of the sun are parallel to the mirror's optical axis. Either the equatorial or the azimuth-zenithal system of rotation may be applied. In the equatorial system the mirror rotates at a speed of one revolution in 24 hours, its angle of slope equalling the latitude of the given locality.

In accordance with the annual inclination of the sun another movement of the mirror is necessary to ensure that its optical axis be parallel to the sun's rays. This second movement is very slow, and can be effected stepwise once in 24 hours.

In the azimuth-zenithal system the mirror simultaneously rotates around both the vertical and the horizontal axes with specific uneven angular velocity.

The parabolic-cylinder mirrors can be rotated only at a constant speed, the angle of slope equalling the latitude of the given locality. This quite essential simplification of the system is, however, achieved by a certain loss of the radiation stream. Under this system the sun's rays are perpendicular to the mirror's generatrix only on the equinoxes; at other times they are inclined. The maximum loss of the radiation stream on account of this incline may run to about 15 per cent.

In choosing the type of installation many diverse factors have to be considered, which may be reduced to three main ones; cost of the installation, cost of its maintenance, and its capacity. It is now possible to calculate the capacity of solar installations with quite sufficient precision for practical purposes.

The following table gives approximate efficiency values (in percentages) for three different types of solar installations designed to work in the summer in the Tashkent area.

Type of installation	*Function*			
	Heat water to 60-70° C.	*Boil water*	*Production of 2-3 atmospheres steam*	*Production of 10-12 atmospheres steam*
Paraboloidal, with 500-700-fold concentration	65-70	64-69	62-67	60-65
Parabolic-cylinder with 30-60-fold concentration	55-60	45-50	40-45	25-30
Plane collectors:				
1 glass	40-45	0-5	—	—
2 glasses	40-45	5-10	—	—
3 glasses	40-45	10-15	5	—

It should be borne in mind that, owing to the inclination of the rays, 1 m.^{2} of plane collector receives less radiation than 1 m.^{2} of mirror. Besides, the plane collectors can work neither in cold weather nor when the solar radiation stream is insignificant.

Though the aforesaid factors depend upon concrete conditions one can give some general considerations concerning the possible sphere of the application of the installations.

STEAM PRODUCTION

Only mirror installations can be used profitably. Paraboloidal installations can produce high-pressure steam, and should be used for the production of steam from about 5 atmospheres upwards. Since parabolic-cylinder installations are cheaper than paraboloidal they may be more profitable for the production of low-pressure steam of up to 5 atmospheres.

The installation (see plate III a) was built by our institute 1947 in Tashkent. It has a paraboloidal mirror 10 m. in diameter, with the angle slope of its rotation axis equalling the local latitude. The screw adjusting the inclination of the mirror in accordance with the inclination of the sun is turned by hand once in 2 days. The reflector is a thin-walled reinforced concrete paraboloidal bowl to which sheets of silvered window glass are glued. As the mirror is large, the radius of curvature of its surface is so big that the glued strips getting slightly deformed solidly adhere to the concrete surface. Hence the mirror when well made is very strong; it can withstand the impact of fairly hard blows with a stone, and only time may unglue its silver coating and blacken it. In the focal plane of the glass a tubular boiler is set. The geometric concentration of the rays here is about 500. The boiler's capacity is 50-60 kg. of steam per hour, the steam pressure 7 atmospheres.

Numerous experiments have been carried out in using this installation for the production of steam for a cannery's technological needs; for working an absorption refrigerator; for operating a regenerative distiller; for heating a laboratory, and for other purposes.

Defects of this kind of installation are that its cost rises faster than its capacity, and that it cannot have a high capacity. Investigations of the force developing in separate parts of the installation owing to aerodynamic loads show that it does not pay to make such mirrors in sizes above 25 m. in diameter.

After comprehensive research our laboratory has developed a new original design of a large solar installation whose boiler will produce 18 tons of steam per hour, or 38,000 tons per year. Such installations solve the problem of exploiting solar energy on a large scale.

DEMINERALIZATION OF SALT WATER

This is one of the chief tasks of helio-engineering. Many places in the arid zones have ground water which,

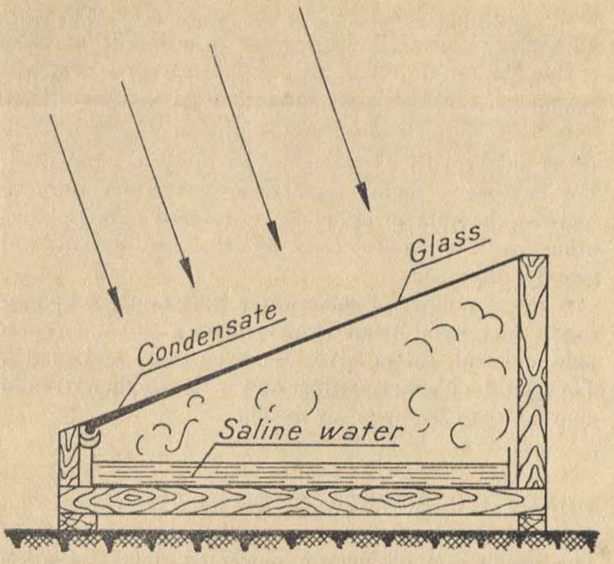

Fig. 1. Flow sheet of a simple saline water distiller.

owing to its large salt content, is unsuitable for drinking. Our laboratory's experiments and calculations show that of the existing water demineralization methods the most practical is distillation. Where there is no local fuel, solar energy should be used.

There are many different systems of solar distillers. They can be sub-divided into (a) regenerative and (b) non-regenerative.

Non-regenerative distillers are simple in design, and are usually made like plane collectors. In the simplest ones a pan filled with saline water is placed at the bottom of the collector and the water is evaporated by the heat of the sun's rays. Touching the glass the vapour condenses and runs down into a trough (Fig. 1). The disadvantage of these distillers is their low output efficiency: 2-3 litres of distilled water per m.^{2} of glass surface on a sunny summer day. They can be used when small quantities of water have to be distilled. Fig. 2 gives the results of testing such a distiller.

When larger quantities of distilled water are required it is more profitable to use regenerative solar distillers. They are a combination of a solar installation producing 7-15 atmosphere steam and of a distiller itself, of the kind used for distilling sea water on ships.

In 1951 and 1952 our laboratory had tested in Tashkent a 3-stage distiller (see plate III b) which received steam from a paraboloidal solar installation with a mirror surface of about 80 m.^{2}. It produced about 1,000 litres of distilled water per day, using 1 kg. of steam per 2.5 litres of distilled water. Calculations based on experimental data have shown that the cheapest way to produce distilled water for livestock grazing in remote pastures in the Kara Kum Desert, is by using multistage distillers receiving steam from paraboloidal solar installations. The following variants were compared in the experiments: (a) bringing up water in motor trucks; (b) distilling water by long-haul fuel; (c) distilling water by solar radiation using: (i) a flat plate horizontal distiller; (ii) a flat plat inclined distiller; (iii) a regenerative distiller with a paraboloidal mirror.

The projected large 18-tons per hour solar installation, mentioned above (page 154), will be capable of producing about 75,000 tons of distilled water and 12,000 tons of ice a year.

BOILING WATER COOKING

For these purposes it is profitable to use installations with parabolic-cylinder or with inaccurate paraboloidal mirrors. Of the various installations for a family of 3-5 persons, developed and tested by us, we can recommend one with a paraboloidal aluminium mirror 1.2 m. in diameter (see plate III c). It produces about 6 litres of boiled water per hour, can cook a dinner, and distil 6 litres of water a day. It is handy for expeditions. On a sunny day it can do the work of a 600 watt electric stove. The U.S.S.R. State Optical Institute has constructed a number of solar kitchens with paraboloidal cylinder mirrors which, however, are less convenient than paraboloidal ones. Our institute has recently constructed in Tashkent an installation with a 12 m.^{2} parabolic-cylinder mirror, producing 400 litres of boiled water per day (see plate III d).

HEATING HOUSES

Steam heating with solar paraboloidal installations may prove profitable in regions where the heating season is short. The mirror installations, however, should be used as multiple-purpose plants. In the summer they can produce technological steam for seasonal consumers and in the last clear days before the heating season should be switched to the heat accumulator, which can be additionally charged on cold

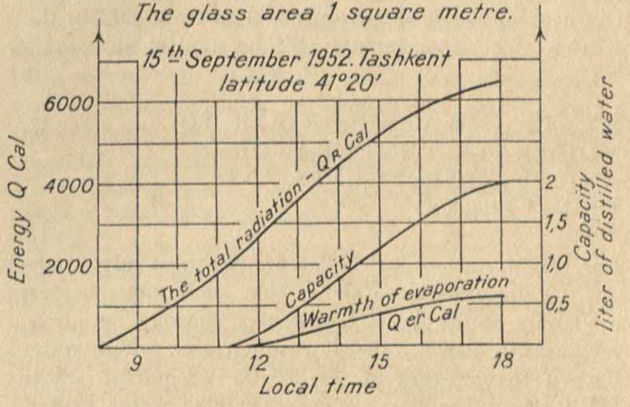

Fig. 2. Results of testing the simple distiller.

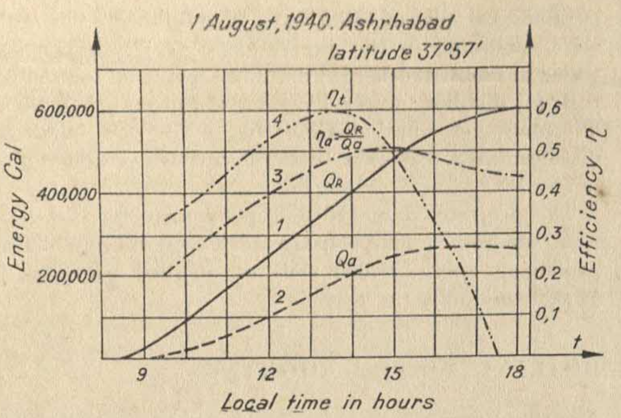

Fig. 3. Results of testing a 100 m.^{2} water heater. (1) The total radiation received per 100 m.^{2} of surface of solar collector. Q cal. (2) Energy accumulated by water Q_a cal. (3) Average efficiency — $\eta_a = \frac{Q}{Q_a}$. (4) Efficiency $\eta_t = \frac{dQ}{dQ_a}$.

but clear days. We carried out successful experiments with such an accumulator in the winter of 1952, and these experiments are continuing. An interesting arrangement of this sort would be to have the installation work as a heating plant in the winter and a cooling plant (for cinemas, hospitals, houses) in the summer.

ICE-MAKING

Our laboratory has obtained ice from an absorption refrigeration plant receiving steam from the abovementioned paraboloidal solar installation with the 80 m.^{2} mirror. In 1953, the refrigerating plant produced 250 kg. of ice per day. Experiments in obtaining refrigeration with the aid of plane collectors showed these installations to have a low efficiency.

It is possible, however, that such installations will be useful for air conditioning buildings during the hot season of the year. This question is of great importance as in the arid regions the population suffers from the heat in the summer no less than from cold in the winter. The experiments will be continued.

HEATING WATER OR AIR TO MODERATE TEMPERATURES AND DRYING FRUITS AND VEGETABLES

For this purpose plane collectors are most advantageous. Long experience shows that such water heaters are surely profitable for bathhouses, showers, laundries, restaurants, dairies, sheep washing, etc., where water with a temperature of 40°-60° C. is required. Plate III e shows the flow sheet of a solar water heater. Different variants of such heaters have been developed.

In conditions such as those prevailing in Tashkent or Ashkhabad, if water heated to 50°-60° C. is needed 7-8 months in the year, the lower half of the heater should be covered with one glass plate and the upper with two. Fig. 3 gives the results of testing such a water heater with a 100 m.^{2} surface built in Ashkhabad. For heating to higher temperatures it is necessary to increase the number of layers of protective glass plates, otherwise the productivity of the installation will greatly diminish.

A large number of solar water heaters are functioning in the central Asian districts of the U.S.S.R. Vegetable and fruit driers have also been built and tested. They yield a cleaner product and with a higher vitamin content than by open air drying.

ELECTRIC POWER PRODUCTION

The production of electric power by solar radiation may be profitable only in special cases, when electricity is not required uninterruptedly. For this purpose it would now be profitable to use an installation working on 15-25 atmosphere steam produced by solar paraboloidal mirror installations. Low-potential plane-collector installations would be bulky and expensive for this purpose, since in the arid zones it is difficult to maintain an economically profitable difference of temperature between the cold and warm sources.

To maintain a constant supply of power by accumulating it by existing methods or with the aid of a reserve fuel installation is complicated and expensive. Therefore the exploitation of solar energy is profitable for such purposes which do not require a strictly scheduled and uninterrupted supply of electricity.

HIGH TEMPERATURE INSTALLATIONS

Such installations for industrial use are now being successfully tested in a number of countries. It should be noted that small workshops, too, may use similar installations for certain purposes, such as melting small quantities of metal, welding thin articles, soldering on hard-alloy cutters, etc. Such experiments were carried out by our laboratory with the installation shown on plate III f.

CONCLUSION

The exploitation of solar radiation for technical purposes may be profitable in a number of cases and has particularly great prospects for arid zones. There are tested installations which can be used for heating, boiling and distilling water, cooking food and making ice.

As multiple purpose plants they may in some cases prove profitable for heating and air-conditioning houses. The important task is to construct a cheap solar engine for lifting water for irrigation.

In conclusion, the exploitation of solar energy should develop both along the line of using a large number of installations for individual consumption, and of constructing large installations for public use. There are no physical or technical difficulties in the way, although economy is often an obstacle. But, considering the great social importance of the extensive exploitation of solar energy, its development should not be made too dependent on economic considerations.

LE RAYONNEMENT SOLAIRE : EXPÉRIMENTATION, POSSIBILITÉS ET PERSPECTIVES D'EXPLOITATION

par

V. A. Baum

RÉSUMÉ

Dans la plupart des régions arides, le ciel est constamment clair pendant la plus grande partie de l'année. Ces régions se prêtent donc parfaitement à la mise en valeur de l'énergie solaire. L'auteur passe en revue les différentes manières d'utiliser cette énergie et constate que, dans l'état actuel de nos connaissances, les seuls procédés efficaces sont ceux qui la convertissent en chaleur.

Le Laboratoire héliotechnique conduit depuis un certain nombre d'années des recherches sur l'exploitation de l'énergie solaire, et l'auteur en résume les conclusions.

Les installations peuvent être réparties en deux catégories selon qu'elles comprennent ou non un dispositif de concentration des rayons.

Les premières servent au chauffage de l'eau, au séchage des légumes et des fruits, au chauffage de l'air et à divers autres usages n'exigeant qu'une température modérée. Au contraire, pour obtenir des températures de plus de 100°, il faut concentrer les rayons du soleil au moyen de miroirs en verre ou en métal. Les possibilités d'emploi de ces dispositifs sont d'autant plus larges qu'ils sont pratiquement indépendants de la température de l'air ambiant, si bien qu'on peut s'en servir en hiver. Les miroirs cylindro-paraboliques permettent d'obtenir des coefficients de concentration de 20 à 70 et les miroirs paraboliques proprement dits des coefficients de 300 à 5.000 et au-delà. Il est bien entendu nécessaire que les miroirs soient soumis à une orientation qui maintienne leur axe optique parallèle à la direction du rayonnement solaire.

Un tableau donne les rendements approximatifs de trois types d'installations destinées à fonctionner en été dans la région de Tachkent.

Pour produire de la vapeur à haute pression, il faut recourir à des miroirs paraboliques. Pour la production de vapeur à basse pression, il est en général indiqué d'utiliser des miroirs cylindro-paraboliques, car ils sont meilleur marché. La figure 1 représente une installation de production de vapeur à haute pression équipée d'un miroir parabolique de 10 mètres de diamètre. L'auteur explique comment ce miroir a été construit ; un nouveau modèle mis au point au laboratoire permettra d'équiper de grandes installations qui produiront 18 tonnes de vapeur à l'heure.

La déminéralisation de l'eau salée est également l'un des principaux objectifs de l'héliotechnique. Des travaux effectués au laboratoire ont montré que la distillation est le plus pratique des procédés connus. On peut se servir de collecteurs plans sans dispositif de concentration, mais le rendement est faible. Pour traiter de grandes quantités d'eau, le mieux est de combiner une installation produisant de la vapeur sous 7 à 15 atmosphères et un appareil de distillation. La figure 4 représente un appareil de distillation fractionnée à trois étages qui a été expérimenté par le laboratoire à Tachkent en 1951 et en 1952. Des calculs fondés sur les résultats de ces essais ont montré que la manière la plus économique de produire de l'eau douce pour la culture de plantes fourragères dans les régions écartées du désert de Karakum consiste à employer des appareils de distillation fractionnée utilisant la

vapeur fournie par une installation à miroirs paraboliques.

Ce sont les installations à miroirs cylindro-paraboliques ou voisins du paraboloïde qui conviennent le mieux aux usages domestiques (ébullition de l'eau et cuisine). La figure 5 représente un appareil de ce genre mis au point au laboratoire.

Des recherches fructueuses ont aussi été menées sur d'autres applications de l'énergie solaire (chauffage et réfrigération de locaux, production de glace, chauffage d'eau ou d'air à des températures modérées, séchage de fruits et légumes). La production de courant électrique ne serait avantageuse que dans des cas particuliers, lorsque les besoins correspondent aux disponibilités.

L'auteur conclut que l'exploitation de l'énergie solaire pourra rendre de grands services, en particulier dans les régions arides. A l'heure actuelle, la tâche la plus urgente est la construction d'un moteur solaire à bon marché pour le puisage de l'eau d'irrigation. En raison du grand intérêt qu'une large utilisation de l'énergie solaire présente sur le plan social, sa mise en valeur ne devrait pas dépendre trop étroitement de considérations économiques.

RADIACIÓN SOLAR: EXPERIMENTOS, POSIBILIDADES Y PERSPECTIVAS DE SU EXPLOTACIÓN

por

V. A. BAUM

RESUMEN

En la mayor parte de las regiones áridas, el cielo está normalmente despejado casi todo el año. Por consiguiente, esas regiones son muy adecuadas para el aprovechamiento de los recursos energéticos del sol. El autor examina los métodos que permiten utilizar la energía solar y llega a la conclusión de que en el estado de los conocimientos actuales, los únicos métodos adecuados son los que transforman en calor la energía radiante.

El Laboratorio Heliotécnico ha venido trabajando durante algunos años en la utilización de la energía solar, y el autor presenta un resumen de los resultados.

Las instalaciones para la explotación de la energía solar pueden dividirse en dos grupos según utilicen o no dispositivos para concentrar los rayos solares.

El primer tipo se emplea para los calentadores de agua, secadores de vegetales y frutas, calentadores de aire y otros aparatos de temperatura moderada. Para obtener temperaturas superiores a 100°, los rayos del sol deben concentrarse por medio de espejos metálicos o de cristal. Al ser prácticamente independientes de la temperatura del ambiente, las posibilidades de uso de esos espejos son mayores, de modo que pueden utilizarse incluso en invierno. La concentración que puede obtenerse con espejos cilindroparabólicos es de 20 a 70 y con espejos parabólicos propiamente dichos de 300 a 5.000 y más. Las instalaciones que funcionan a base de espejos exigen, desde luego, un mecanismo de rotación de manera que los rayos del sol incidan paralelamente al eje óptico del espejo.

En el texto figura una tabla que muestra los valores de rendimiento de tres tipos diferentes de instalaciones destinadas a funcionar durante el verano en la región de Taskent.

Para producir vapor a alta presión es necesario utilizar espejos parabólicos. Para obtener vapor a baja presión son generalmente indicadas las instalaciones cilindroparabólicas, por ser más baratas. En la figura 1 se ve una instalación de alta presión con un espejo parabólico de 10 m de diámetro. En este trabajo el autor describe la construcción del espejo. El Laboratorio ha preparado los planos para una gran instalación que producirá 18 toneladas de vapor por hora.

La desmineralización del agua salobre es una de las tareas más importantes de la helioingeniería. Los trabajos efectuados en el Laboratorio han demostrado que la destilación es el más práctico de los métodos existentes. Pueden utilizarse colectores planos sin dis-

positivos de concentración, pero son poco eficaces. Para producir grandes cantidades de aga, el mejor método consiste en una combinación de una instalación solar que produzca vapor a 7 o 15 atmósferas y un destilador. En la figura 4 puede verse un destilador de tres fases ensayado por el Laboratorio en 1951 y 1952 en Taskent. Los cálculos basados en los ensayos demostraron que la manera más económica de obtener agua para el ganado que pasta en regiones remotas del desierto de Karakum consiste en emplear un destilador multifase que funcione a base del vapor obtenido por medio de una instalación de espejos parabólicos.

Para hervir agua y para la cocción de alimentos, las mejores instalaciones son los espejos cilindroparabólicos o los quasiparabólicos de escasa corrección. En la figura 5 puede verse una instalación construída en el Laboratorio con ese objeto.

También se han llevado a cabo provechosas investigaciones sobre los posibles usos siguientes: calefacción y refrigeración doméstica, fabricación de hielo, calentamiento de agua o de aire a temperaturas moderadas, desecación de frutas y vegetales. No obstante, la producción de energía eléctrica, sólo resultaría económica en casos especiales, cuando la energía solar disponible bastara para satisfacer las necesidades.

El autor concluye diciendo que se abren grandes perspectivas para la explotación de la energía solar en las regiones áridas. La tarea más importante en los años próximos es construir un motor barato accionado por la energía solar para elevar el agua de riego. Considerando la gran importancia social de la explotación a gran escala de la energía solar, su desarrollo no debería depender demasiado de las consideraciones económicas.

STRUCTURE DES MACHINES UTILISANT L'ÉNERGIE SOLAIRE

par

Félix Trombe

Les machines utilisant l'énergie solaire doivent être adaptées aux conditions suivant lesquelles cette énergie nous parvient. Nous examinerons donc successivement quelques caractères du rayonnement solaire, son captage par des récepteurs fixes, sa réflexion et son orientation, sa concentration optique, sa réception par les substances.

LE RAYONNEMENT SOLAIRE

L'énergie qui nous parvient du soleil est caractérisée par un rayonnement dont la répartition énergétique en fonction de la longueur d'onde est située en grande partie dans le domaine des radiations visibles. On voit sur la courbe 1 (fig. 1), que le maximum d'émission énergétique est situé aux environs de 0,47 μ. Cette courbe est assez comparable à celle que l'on obtiendrait avec le rayonnement du corps noir porté à 6.200° absolus (courbe 2, fig. 1).

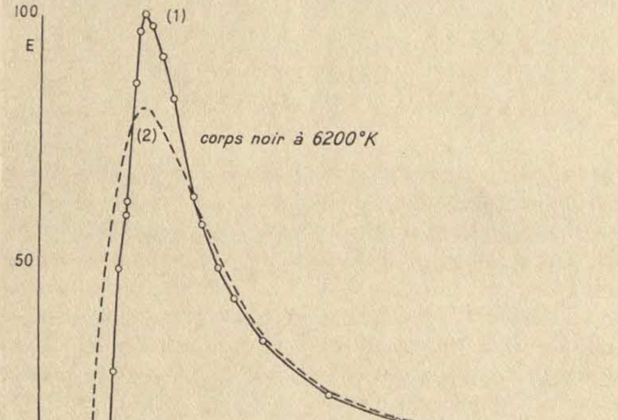

Fig. 1. Répartition de l'énergie solaire et de celle du corps noir à 6.200° K en fonction de la longueur d'onde λ. (Unités arbitraires.)

La surface du soleil émettrait donc comme un corps noir à 6.200° K[1], c'est-à-dire que chaque centimètre carré de cette surface émet dans l'espace une énergie W (voir tableau, col. 4) de plus de 8 kW. Au voisinage de la stratosphère terrestre, en raison de la distance du soleil (149 millions de km en moyenne), elle n'est que de 0,135 watt/cm^2 (1.350 watts au mètre carré), soit de l'ordre de 60.000 fois moins.

t° C	*T° K*	*λ max (μ)*	*W (W/cm^2)*
6.000	6.273	0,46	8.840
5.000	5.273	0,55	4.410
4.000	4.273	0,67	1.900
3.000	3.273	0,88	655
2.000	2.273	1,27	152
1.000	1.273	1,79	15,0
500	773	3,73	2,04
100	373	7,73	0,110
0	273	10,6	0,0317
— 50	223	12,9	0,0141
— 100	173	16,7	0,00511

Le soleil, pour un observateur terrestre, présente en moyenne un diamètre apparent de l'ordre de 32′ d'arc. Pour un observateur situé sur le soleil, la terre aurait un diamètre apparent infime. Il s'ensuit que les directions suivant lesquelles nous apercevons le soleil, à un instant donné, des différents points du globe terrestre, sont pratiquement parallèles.

Nous avons dit que le soleil vu de la terre avait un diamètre apparent de 32′ d'arc ; son image dans un système optique convergent quelconque de distance focale f aura, de ce fait, un diamètre de l'ordre de $f/100$.

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[1] On sait que le rayonnement du corps noir est proportionnel à la quatrième puissance de sa température absolue (loi de Stephan).

La réflexion du rayonnement solaire sur un miroir plan de dimensions très petites ou le passage de ce rayonnement à travers un trou de faible diamètre conduira aussi, d'après ce qui précède, à une divergence telle que l'on ait sur un écran perpendiculaire, placé à une distance d du trou ou du miroir, un disque lumineux de diamètre approximativement égal à $d/100$ (d étant évidemment très grand par rapport au diamètre du trou ou aux dimensions du miroir).

On ne peut donc conserver très loin après une réflexion sur un miroir plan la densité énergétique initiale du rayonnement du soleil. Nous reviendrons sur cette question à propos des appareils d'orientation.

La présence du rayonnement solaire est non seulement intermittente mais incertaine sur bien des points de la terre. Il existe, par contre, entre les tropiques et les zones tempérées, d'immenses territoires qui jouissent d'un ensoleillement exceptionnel. On peut y dénombrer trois cents jours par an de soleil sans un nuage, ce qui conduit à un bilan annuel de trois mille heures de présence du rayonnement solaire. C'est dans de telles régions qu'il pourrait être éventuellement utilisé industriellement.

LA RÉCEPTION DU RAYONNEMENT SOLAIRE PAR DES APPAREILS FIXES

Le dispositif le plus classique est celui qui utilise ce que l'on appelle l'effet de serre. Le tableau, p. 160, qui donne les émissions énergétiques W du corps noir pour différentes températures, montre qu'un corps noir soumis, à l'air libre et en l'absence de tout échange thermique par convection et conduction, au rayonnement solaire peut atteindre, au plus, une température de l'ordre de 100°. En effet, dans ces conditions, il dissipe par rayonnement dans un angle solide de 2π stéradians environ 0,110 watt par centimètre carré ou 1.100 watts au mètre carré, ce qui représente à peu près la densité d'énergie qui peut être reçue du rayonnement solaire normalement à sa direction. En réalité à la surface du sol, les pertes par conduction et convection et aussi le fait que les matières chauffées ne reçoivent pas le rayonnement comme un corps noir conduisent, suivant les cas, à des températures maxima de 40 à 60°.

Le captage des calories du soleil par effet de serre consiste à recouvrir la substance à chauffer d'une lame (verre ou liquide non volatil) transparente aux rayons du soleil et opaque aux rayons de grande longueur d'onde qu'elle émet. On trouve dans la colonne 3 du tableau la longueur d'onde λ_m correspondant au maximum d'émission énergétique des corps noirs portés à différentes températures[1]: pour $t = 100°$ C., λ_m est de l'ordre de 8 μ. Or le verre et l'eau absorbent complètement les rayonnements de longueurs d'ondes supérieures à quelques μ alors qu'ils laissent passer la presque totalité du rayonnement solaire.

Fabry [2][2] démontre que l'échauffement obtenu sous une lame transparente fonctionnant dans les conditions précédentes est égal à celui que l'on aurait à l'air libre si la densité énergétique du soleil était deux fois plus grande. On devrait donc atteindre d'après la loi de Stephan 150° C. environ. L'expérience montre que 100 à 110° C. sont aisément obtenus ; certains essais de J. Duclaux[3] dans des solutions aqueuses sous tension de vapeur ont même donné 130° C.

Le captage direct du rayonnement solaire dans les conditions précédentes est évidemment le plus commode, le moins coûteux et il s'impose toutes les fois que l'obtention d'une température de 60 à 75° C. est suffisante. Il faut distinguer, comme nous verrons plus loin, entre la température maximale obtenue dans une expérience et la température utilisable, c'est-à-dire celle qui est réellement obtenue lorsqu'on demande à la machine de fournir des calories. En particulier, il semble difficile, par chauffage direct sans concentration, de faire bouillir de l'eau à 100° C. avec un rendement acceptable.

Un autre fait, celui de l'incidence variable du rayonnement solaire, vient encore diminuer la température moyenne que l'on peut espérer atteindre au cours d'une journée.

Le chauffage direct permet le chauffage et la distillation de l'eau et également le chauffage de l'air, base de la climatisation des maisons.

Dans différents pays, et particulièrement en Amérique, fonctionnent sur les principes précédents de nombreuses installations. Des recherches sont en cours pour améliorer encore leur prix de revient et leurs conditions d'utilisation.

RÉFLEXION ET ORIENTATION DU RAYONNEMENT SOLAIRE

Les rayons solaires réfléchis par un miroir plan donnent sur un écran une zone à énergie constante entourée d'un halo à énergie décroissante vers l'extérieur ; la surface de la zone à énergie constante décroît à mesure que l'on s'éloigne du miroir.

La figure 2 schématise, avec une valeur arbitraire du diamètre apparent du soleil, exagérée pour simplifier la figure, le résultat obtenu pour une des dimensions du miroir considéré.

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[1] Ces longueurs d'onde sont calculées par application de la loi de déplacement de Wien : $\lambda m T$ = Cte.

[2] Les chiffres entre crochets renvoient à la bibliographie, à la fin de ce rapport.

[3] Inédit.

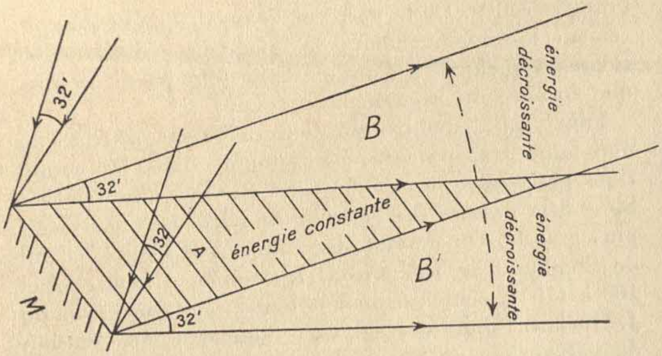

Fig. 2. Répartition de l'énergie solaire réfléchie par un miroir plan.

Dans la zone centrale A, la densité énergétique restera constante et égale à celle du soleil, au facteur de réflexion près, alors que dans les zones symétriques B et B' l'énergie est constamment décroissante de la partie centrale vers les parties latérales.

C'est à l'intérieur du faisceau A que doivent toujours se trouver les appareils utilisant le rayonnement transmis par le réflecteur plan, et ceci pour toutes les positions de ce réflecteur.

Si l'on veut orienter le rayonnement solaire dans une direction déterminée pendant dix à douze heures par jour, il est nécessaire que le réflecteur puisse faire des angles de + 45° et — 45° avec la direction du rayon réfléchi. Les dimensions du faisceau à énergie constante en seront d'autant réduites, et il faut tenir compte de ce facteur.

La réalisation d'un réflecteur véritablement plan est difficilement obtenue avec des surfaces métalliques. Par contre, les lames de verre à faces parallèles peuvent avoir des qualités optiques largement suffisantes pour que la réflexion du rayonnement solaire reste assez correcte. Le parallélisme de leurs faces peut être excellent, mais elles présentent parfois de légères courbures suivant une de leurs dimensions.

Par un choix judicieux des glaces, la société de Saint-Gobain, en France, a pu donner au Laboratoire de l'énergie solaire de Mont-Louis (Pyrénées-Orientales, France) (voir hors-texte IV *a*), des plans réflecteurs de 50 × 50 cm d'une épaisseur de l'ordre de 6 mm et ne présentant pas, en général, de dispersion angulaire, pour les rayons réfléchis, supérieure à 5' d'arc.

La dimension des unités réfléchissantes ne peut guère dépasser 50 × 50 cm. On peut alors adopter des épaisseurs de l'ordre de 6 mm, suffisantes pour que les glaces, dans les différentes positions que leur assigne l'orientation du rayonnement, ne prennent pas de courbure notable sous l'action de leur propre poids.

Les glaces précédentes sont extrêmement robustes, à la fois au point de vue thermique et au point de vue mécanique. Par contre, des glaces ayant 1 m × 1 m, forcément plus épaisses, sont déjà fragiles.

Le choix de la matière réfléchissante supportée par la lame de verre est pratiquement limité à l'argent ou à l'aluminium. Nous avons vu que l'aluminium métallique, même si sa surface est traitée pour obtenir un facteur de réflexion maximum, n'est pas très facilement utilisable pour réaliser des réflecteurs plans. On pourrait, par contre, aluminiser par vaporisation thermique les surfaces de verre du côté où la réflexion doit s'effectuer. On évite ainsi la traversée du verre, l'absorption de l'ultraviolet dans sa masse et, éventuellement, la dispersion angulaire résultant d'une mauvaise planéité de la face arrière de la lame. La seule incertitude est la durée de résistance de cette pellicule d'aluminium directement exposée aux agents atmosphériques. On pourrait, évidemment, tenter de la protéger par un vernis présentant la transparence voulue.

La réflexion sur dépôt superficiel d'aluminium a été, comme nous le verrons, adoptée pour des réflexions à courte distance de rayonnements convergents issus de miroirs paraboliques.

Les surfaces réfléchissantes d'argent sont nécessairement disposées en arrière de la lame de verre, les couches étant chimiquement trop fragiles pour subir directement l'action de l'atmosphère et des intempéries. Un vernis ne suffirait d'ailleurs pas à les protéger et l'on a eu recours à un cuivrage électrolytique de l'argent. Le cuivre est lui-même isolé par le dépôt d'un vernis de nature convenable.

Une telle disposition — verre argenté sur la face arrière par dépôt chimique, cuivrage de l'argent et protection du cuivre par un vernis — s'est montrée d'une très grande robustesse. Certaines glaces de nos appareils orienteurs de Mont-Louis sont depuis cinq ans exposées, été comme hiver, aux intempéries et ne montrent pas de détérioration notable. C'est cette expérience très probante sur les surfaces réfléchissantes de verre argenté et cuivré qui nous conduit maintenant à préconiser leur emploi pour des réalisations de plus grande importance.

Les surfaces de verre réfléchissantes ainsi réalisées conservent toujours un facteur de réflexion excellent et sont d'un nettoyage très facile (si ce nettoyage n'est pas déjà effectué par les intempéries elles-mêmes).

Il semble, à première vue, défectueux de faire traverser par le rayonnement solaire deux fois l'épaisseur de la lame à faces parallèles. On perd, évidemment, dans cette opération la quasi-totalité de l'ultraviolet provenant du soleil, mais ce rayonnement ne représente qu'une très faible part de l'énergie totale reçue et, en définitive, le facteur de transmission d'une lame de verre clair argentée sur la face arrière reste toujours, pour les épaisseurs que nous avons indiquées (5 à 8 mm), légèrement supérieur (82-85 %) à celui que peut donner une surface d'aluminium (80 %). On récupère, en effet, avec un très faible décalage latéral, les pertes d'énergie dues aux réflexions vitreuses.

La réfraction du rayonnement incident et du rayonnement réfléchi n'a pas non plus d'influence sur l'orientation finale du faisceau réfléchi. Il n'en serait pas de même, évidemment, si l'on avait affaire à un miroir convergent.

La dimension des glaces élémentaires (50 × 50 cm) imposée par les conditions requises de robustesse et de poids, qui conditionnent le prix de revient, est évidemment faible. Il convient de grouper, en réglant leur parallélisme, les glaces élémentaires sur un support commun métallique qui sera pourvu d'axes convenables pour l'orientation de l'ensemble.

Il a été réalisé à Mont-Louis un orienteur de 135 m² groupant cinq cent quarante glaces planes de 50 × 50 cm. Cet appareil, relativement grand et dont le principe est imposé par le lieu même de son installation, n'est peut-être pas le plus économique, si l'on rapporte son prix de revient au mètre carré de rayonnement solaire orienté. Il est probable que des machines moins puissantes construites avec des éléments de série permettront de réaliser encore des abaissements substantiels du prix de revient du kilowatt solaire installé. En effet, les dispositifs d'orientation et d'asservissement de chaque machine ne représentent, même pour des unités de l'ordre de 30 m², qu'une faible part du prix de revient de l'ensemble.

Le guidage des appareils orienteurs doit s'inspirer de principes simples. Il faut proscrire, autant que possible, de ces machines, tous les mécanismes de précision et, en particulier, tout asservissement dit "astronomique", qui ne peut être efficace que s'il est parfaitement réglé.

La méthode de beaucoup la plus simple consiste à obliger le rayon réfléchi par le miroir orienteur à conserver une direction déterminée. Le contrôle de ce rayon réfléchi s'effectue très simplement par quatre cellules photo-électriques groupées par paires diamétralement opposées (C_1C_3, C_2C_4, fig. 3). Ces cellules entourent un écran E où se forme normalement, si la position de l'orienteur est correcte, une image du soleil donnée par une lentille située sur le trajet du rayonnement réfléchi. L'appareil orienteur étant, en général, supporté par deux axes perpendiculaires, on chargera chaque paire de cellules C_1C_3, C_2C_4 de commander dans les deux sens de rotation un des mouvements de l'orienteur autour de ses axes. D'après nos expériences de Mont-Louis il suffit d'un très faible décalage de l'image pour provoquer la mise en place du plan orienteur.

Naturellement, on peut choisir entre différentes solutions pour établir la liaison entre les cellules et les mécanismes modifiant la position de l'orienteur: par exemple, relai à cascade de contact "tout ou rien" avec temporiseurs d'inversion, ou amplification électronique du courant de cellule, puis commande électrique progressive type amplidyne, ou encore commande progressive de piston à huile à partir du relai électronique.

Tous ces appareils, relativement peu coûteux, installés dans les différents montages solaires de Mont-Louis, ont déjà fait leurs preuves et seule la "tenue en service" après de longues années permettra de mieux définir leurs avantages respectifs.

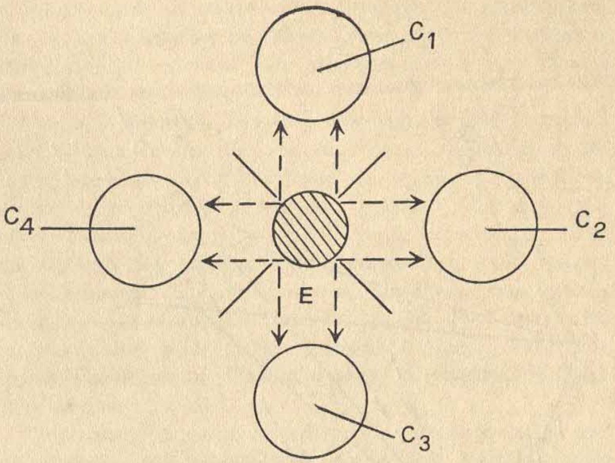

Fig. 3. Contrôle du rayonnement réfléchi par un ensemble de cellules photo-électriques.

LA CONCENTRATION OPTIQUE DU RAYONNEMENT SOLAIRE

L'expérience d'Archimède répétée par Buffon concrétise le principe du regroupement optique des rayons solaires. On choisit une surface réceptrice qui sera le "foyer" du système et l'on superpose sur cette surface, à l'aide de nombreux réflecteurs, des taches de soleil.

Lorsque ces réflecteurs deviennent très petits et que leur nombre devient très grand, on est conduit, pour des raisons d'accumulation énergétique maximale sur la tache de soleil, à les rendre tangents à un paraboloïde fictif imposé par la distance focale choisie préalablement.

Nous disposons, pour cette accumulation, d'un angle solide de 2 π stéradians qui est celui suivant lequel rayonnera la surface chauffée. On voit, comme le représente la figure 4, que l'étalement de l'image du soleil au plan focal augmente à mesure que l'on s'écarte de l'axe du paraboloïde. Des calculs précis [1, 5] ont permis de se rendre compte de l'importance relative de l'étalement de l'image pour des ouvertures de miroirs paraboliques de 0,2 f, f et 2 f (fig. 5). Pour cette dernière ouverture, l'énergie dispersée en dehors de la tache centrale sera de l'ordre de 20 %.

Au-dessus de l'ouverture de 2 f, les étalements d'image sont tels que l'on n'a pas intérêt, sauf dans des cas particuliers où l'obtention de très hautes températures serait nécessaire, à augmenter encore la surface du paraboloïde réflecteur.

Ce qui précède montre bien, étant donné les ouvertures de miroir nécessaires, qu'il est impossible d'obtenir au foyer une image correcte du soleil. La recherche d'un tel résultat conduirait à des ouvertures certainement inférieures à 0,1 f et l'énergie récoltée serait très insuffisante par rapport à la surface de l'image formée.

L'adoption d'une ouverture égale à 2 f (le diamètre

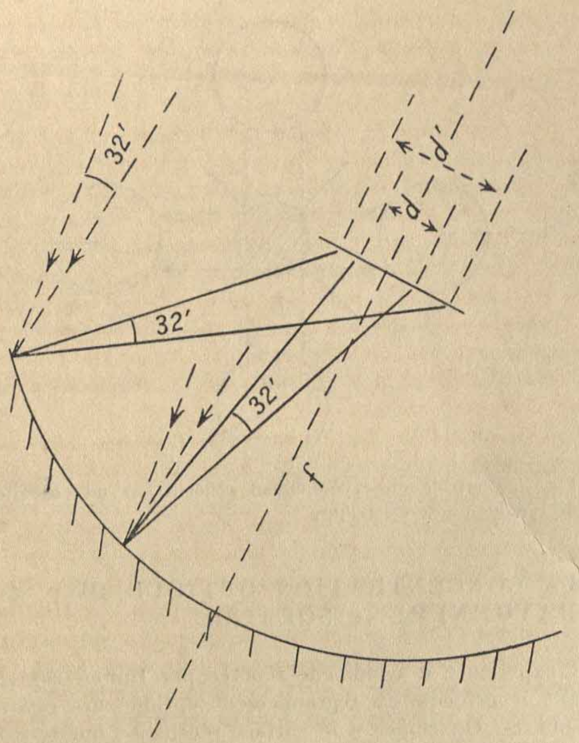

Fig. 4. Étalement de l'image du soleil au foyer d'un miroir parabolique.

du miroir étant égal à deux fois la distance focale) donne un angle de convergence de l'ordre de 100°, ce qui est déjà très important. Dans ces conditions, l'énergie s'étale avec une valeur décroissante sur une tache de diamètre égal à $4\,r$ (fig. 5 et 6), soit deux fois la valeur théorique du diamètre $2\,r$ de l'image solaire. Par exemple, dans le grand appareil de Mont-Louis, de 6 mètres de distance focale et d'ouverture $2\,f$, on ne peut espérer, même dans des conditions idéales, diminuer le diamètre de la tache solaire au-dessous de 12 cm, alors que la dimension de l'image du soleil donnée par les rayons voisins de l'axe du paraboloïde est de 6 cm.

La concentration énergétique maximum que peut donner théoriquement un miroir parabolique parfait d'ouverture $2\,f$ est néanmoins encore considérable.

La surface apparente du miroir est égale à πf^2, alors que la surface de l'image centrale est $\frac{\pi}{4}\,(f/100)^2$. Le rapport des surfaces est de 40.000. Si l'on admet, après les pertes d'énergie par réflexion, 0,075 watt par centimètre carré sur le miroir et 80 % de rendement sur l'image centrale, la densité d'énergie sur cette dernière sera de : $0{,}075 \times 40.000 \times 0{,}8 = 2.400$ watts/cm².

L'examen du tableau 1 montre qu'une telle densité d'énergie correspond au rayonnement du corps noir porté à une température notablement supérieure à 4.000° C.

Il doit donc être possible, même avec un appareil assez imparfait, d'obtenir 3.000 à 3.500° C. sur des substances absorbant bien le rayonnement solaire ou dans des cavités formant corps noir. En effet, à 3.000° C. l'énergie rayonnée par le corps noir n'est que de 655 watts/cm² (voir tableau), soit trois à quatre fois moins que celle qui a été calculée (2.400 watts).

A côté des appareils donnant de hautes concentrations d'énergie solaire, tels que les miroirs paraboliques très ouverts, existent des dispositifs d'utilisation plus facile, les miroirs cylindro-paraboliques, qui donnent néanmoins des températures suffisantes, 500 à 1.000° C., pour différentes utilisations, en particulier pour les cycles thermiques moteurs.

Un miroir cylindro-parabolique est engendré par le déplacement d'une parabole parallèlement à son plan. On obtient ainsi une sorte d'auge concentrant les rayons solaires sur une surface rectangulaire étroite.

L'examen de la figure 4 montre que ce rectangle de petit côté d présentera à droite et à gauche sur une largeur d' un éclairement décroissant. On éviterait en partie cet étalement en utilisant un cylindre à la place du plan récepteur.

Les concentrations que l'on peut obtenir avec un miroir cylindro-parabolique sont assez faibles comparées à celles que donnent le parabolique vrai. Pour une ouverture égale à $2\,f$, l'image aurait une largeur de $f/100$; or, le miroir reçoit l'énergie sur une largeur de $2\,f$. C'est donc une concentration maximum de 200 qui est obtenue avec le cylindro-parabolique au lieu de 40.000 pour l'appareil de révolution. On aurait, compte

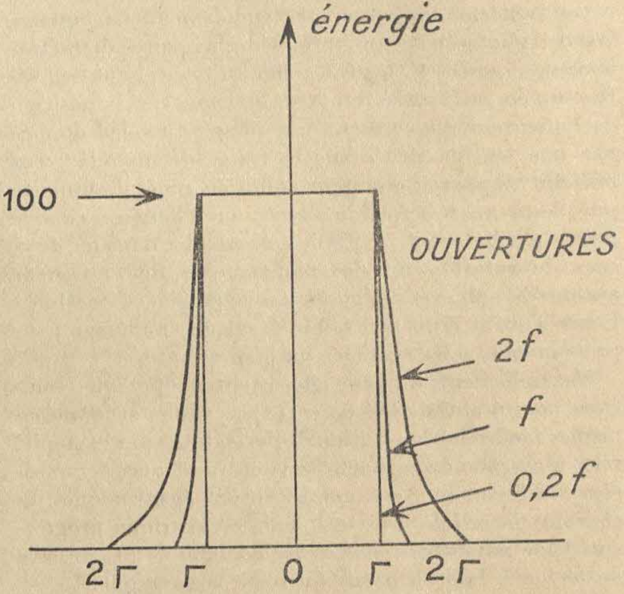

Fig. 5. Répartition de la densité d'énergie réfléchie par un miroir parabolique, dans le plan focal, pour différentes ouvertures du miroir (r = rayon de l'image de la source à haute température donnée par un miroir à faible ouverture ; f = distance focale du miroir).

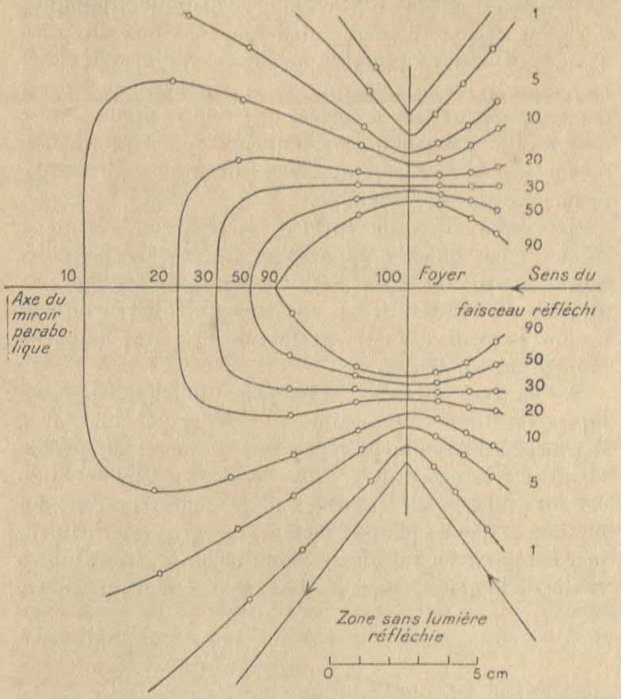

Fig. 6. Répartition, dans un plan méridien, de la densité d'énergie réfléchie par un miroir parabolique (distance focale 6 m, ouverture 2 *f*).

non tenu des aberrations, 0,075 × 200 = 15 watts/cm².

Le tableau ci-dessus donne pour ce rayonnement une température du corps noir de 1.000° C., température suffisamment élevée pour réaliser un cycle thermique moteur d'assez bon rendement.

Le meilleur dispositif de réception du rayonnement solaire par un miroir cylindro-parabolique consiste à disposer sa ligne focale parallèlement à l'axe du monde et à le faire tourner de manière à maintenir son plan de symétrie dans la direction du soleil. On récolte ainsi le maximum d'énergie entre le lever et le coucher du soleil. L'inconvénient est qu'il faut pour suivre le soleil disposer d'un mécanisme convenablement réglé.

Schumann, dans ses montages de chaudière solaire, avait réalisé un miroir cylindro-parabolique très important orienté est-ouest. L'image du soleil restait sur la ligne focale quelle que fût l'inclinaison du soleil à l'est ou à l'ouest, ceci à la condition que l'on réglât tous les deux ou trois jours, ou au moins toutes les semaines, l'orientation du miroir de manière à maintenir son plan de symétrie dans le sens de l'écliptique. L'inconvénient principal était le grandissement exagéré de l'image pour les positions du soleil inclinées vers l'est et vers l'ouest.

Les miroirs paraboliques de révolution ont déjà été réalisés sous différentes formes, verre travaillé optiquement, aluminium poli, et l'on sait par différents travaux, en particulier ceux effectués au Laboratoire de l'énergie solaire de Mont-Louis, que des températures élevées peuvent être atteintes aux foyers de ces appareils.

On peut recevoir le soleil directement sur le miroir parabolique et chauffer les substances directement au foyer ou encore (fig. 7) avec un miroir d'aluminium ou de verre aluminisé agissant à courte distance renvoyer l'énergie sur un foyer F', ce qui permet de traiter en surface des substances pulvérulentes. Néanmoins, il est souvent mal commode de disposer d'une source d'énergie qui se déplace dans l'espace et c'est pour cela, en particulier pour les gros appareils, qu'ont été réalisées l'orientation d'abord, puis la focalisation du rayonnement solaire.

L'orienteur M peut renvoyer les rayons solaires sur un miroir parabolique fixe d'axe soit vertical, soit horizontal (fig. 8).

Les résultats déjà obtenus et les perspectives de recherches ouvertes par l'emploi des hautes températures produites par concentration de rayonnement solaire ont provoqué dans différents pays la réalisation de paraboloïdes réflecteurs à grande concentration d'énergie adaptés à l'utilisation, à leur foyer, du rayonnement convergent. Ces "fours solaires", comme on a l'habitude de les appeler, ont été presque tous, jusqu'à présent, d'assez petites dimensions.

Dans le passé, les "miroirs ardents" et les "verres ardents", d'ouverture assez faible, avaient déjà donné des effets spectaculaires. Durant ces dernières années, des montages variés ont été réalisés dans différents pays, à l'aide de miroirs paraboliques, soit en verre, soit en aluminium.

Pour les premiers, la plupart des expérimentateurs ont pu disposer de miroirs destinés à un autre usage : les miroirs de DCA, d'une qualité déjà remarquable. Pour les seconds, il a fallu faire des études d'emboutissage de tôles d'aluminium dans la forme désirée et donner ensuite à ces tôles, par voie chimique et électrolytique, le poli indispensable.

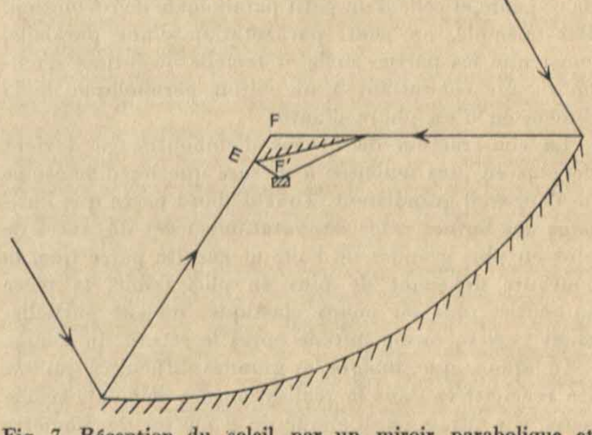

Fig. 7. Réception du soleil par un miroir parabolique et réflexion à courte distance du rayonnement convergent par un miroir plan en aluminium.

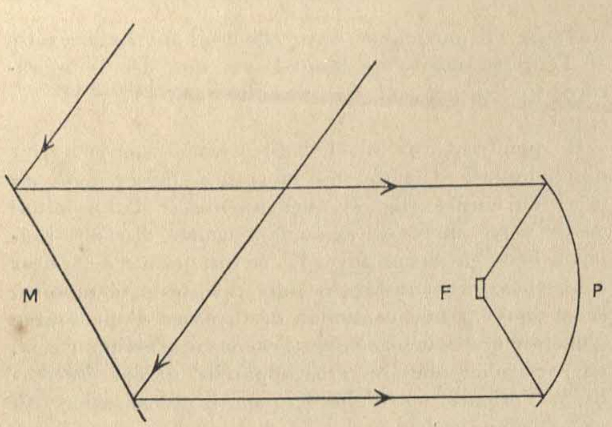

Fig. 8. Réception du rayonnement solaire sur un miroir plan mobile orienteur M, puis sur un miroir parabolique fixe P.

Le problème s'est posé, en même temps, de l'augmentation progressive des dimensions de ces appareils. En effet, les premiers miroirs d'expérience, de quelques mètres carrés de surface, étaient, en général, d'une seule pièce. Il ne pouvait être question, en augmentant les dimensions, de conserver un élément réflecteur unique. La fragmentation de la machine s'effectue de manière rationnelle, suivant le schéma de la figure 9. Le paraboloïde est composé d'un certain nombre de couronnes réflectrices coaxiales (*a*, *b*, *c*, etc.), chacune de ces couronnes étant composée, elle-même, d'éléments identiques entre eux (*a*, *a*′, *a*″, . . ., *b*, *b*′, *b*″, . . ., *c*, *c*′, *c*″, . . ., etc.). On doit donc réaliser autant de types d'éléments réflecteurs qu'il y a de couronnes dans le paraboloïde.

La portion de paraboloïde que représente un élément réflecteur est engendrée par la rotation de la parabole autour de son axe. Il n'existe donc, entre ses différents points, aucune symétrie. On voit l'énorme différence entre la réalisation d'une surface courbe dissymétrique de ce genre et celle d'un petit paraboloïde de révolution. Par exemple, on peut, par rotation d'une parabole, construire les parties mâle et femelle de formes d'emboutissage conduisant à un miroir parabolique de la dimension d'un phare d'auto.

La construction de formes d'emboutissage devient de plus en plus malaisée à mesure que les dimensions de l'appareil grandissent. Tout d'abord parce que l'usinage des formes exige des rotations à des distances de plus en plus grandes de l'axe et ensuite parce que, la courbure devenant de plus en plus faible, la pièce emboutie, plus ou moins élastique, revient partiellement vers sa forme initiale après le retrait du moule.

Indiquons que, malgré les grandes difficultés qui ont été rencontrées dans la réalisation des éléments réflecteurs, un miroir parabolique de 8 mètres de diamètre comportant des couronnes coaxiales et des éléments tels que l'indique la figure 8 vient d'être terminé sous les auspices de la Recherche scientifique appliquée d'Algérie et fonctionnera prochainement aux environs d'Alger. On peut penser, en raison du grand effort technique qui a été fait, que cet appareil pourra donner des températures aussi élevées que celles obtenues avec des miroirs paraboliques de quelques mètres de diamètre et, naturellement, avec un apport d'énergie beaucoup plus considérable.

La construction de surfaces courbes en verre, de formes telles qu'elles puissent se situer dans les différentes couronnes d'un paraboloïde, présente de très grandes difficultés. C'est un principe différent qui a permis la réalisation du grand miroir parabolique de Mont-Louis de 90 m².

Si l'on avait à réaliser d'immenses machines paraboliques récoltant des dizaines de milliers de kilowatts, le procédé d'Archimède repris par Buffon serait probablement très acceptable. Nous avons vu en effet qu'il est fort difficile de faire des plans réflecteurs en aluminium et que les plans réflecteurs de verre, relativement peu coûteux, en raison de l'énorme production industrielle de la glace mince, ne doivent pas avoir, pour être

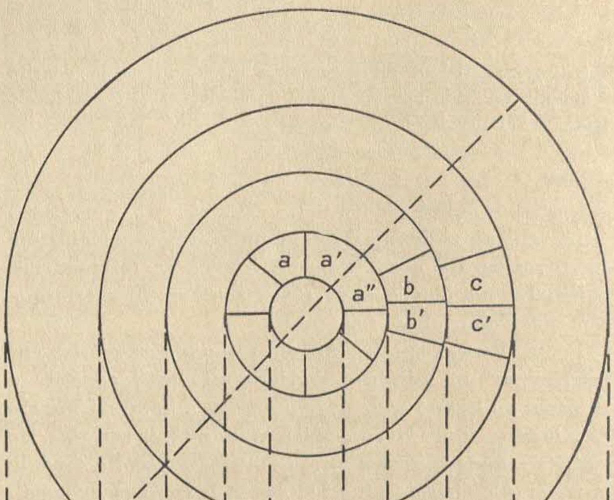

Fig. 9. Disposition des éléments réflecteurs dans un miroir parabolique divisé ; les couronnes coaxiales sont constituées d'éléments identiques : *a*, *a*′, ... *b*, *b*′, ..., *c*, *c*′, ...

thermiquement et mécaniquement robustes, de dimensions supérieures à 0,25 à 0,30 m². On peut alors adopter de la glace de 4 à 8 mm, d'un poids relativement faible et très élastique.

La tache lumineuse donnée sur un écran par les rayons solaires réfléchis par une glace présente, comme nous l'avons indiqué figure 2, différents aspects. Lorsque l'écran s'éloigne de plus en plus de la glace, l'image du soleil devient progressivement identique, à l'intensité lumineuse près, à celle que pourrait donner à son foyer un dispositif optique convergent. Il faut évidemment pour obtenir un tel résultat que l'ouverture du dispositif soit très faible, c'est-à-dire que le diamètre du miroir soit des centaines de fois plus petit que la distance à laquelle on forme l'image.

Placer côte à côte de telles glaces élémentaires pour constituer un paraboloïde de grande ouverture conduit à un nombre de glaces véritablement imposant. Par exemple, pour obtenir à l'aide de glaces planes une concentration énergétique équivalente à celle que pourrait donner un paraboloïde travaillé optiquement, il faudrait au moins vingt-cinq mille de ces glaces élémentaires. Il faudrait donc vingt-cinq mille réglages consistant en des possibilités d'articulation suivant deux directions perpendiculaires.

Un tel montage peut s'amortir pour des installations présentant des surfaces considérables. Encore est-il toujours beaucoup plus coûteux que celui que nous allons décrire et qui a été utilisé pour la première fois à Mont-Louis.

Prenons, par exemple, une glace argentée de 50 × 50 cm et imaginons l'image qu'elle donne sur un écran placé à 25 mètres. Si la glace est de bonne planéité, nous aurons une zone centrale à énergie constante (fig. 2) entourée d'un halo à énergie décroissante, mais dont la surface de la tache lumineuse est notablement supérieure à celle du réflecteur. Courbons maintenant, par une simple pression des doigts en des points convenablement choisis, cette glace de manière à réaliser une surface courbée correspondant grossièrement à un secteur de paraboloïde. On voit, sur l'écran, l'image obtenue se rétrécir considérablement et devenir circulaire. Sa surface totale est alors très inférieure à celle du réflecteur.

C'est l'organisation systématique de cette courbure sous contrainte mécanique (fig. 10) qui a permis la réalisation du grand paraboloïde de Mont-Louis (voir hors-texte IV *b*). Malgré ses dimensions relativement imposantes, cet appareil est encore trop petit pour donner au principe précédent toute son efficacité. Au lieu de glaces de 4 à 6 mm d'épaisseur, glaces qui peuvent convenir pour donner, par courbure mécanique, une sorte de foyer à partir de 25 à 30 mètres, il a été nécessaire d'adopter des épaisseurs de verre telles que la focalisation ait lieu, au minimum, à 6 mètres.

C'est du verre mince argenté, d'épaisseur de 1,5 à 1,7 mm, qui a été employé pour construire le paraboloïde de Mont-Louis. On connaît les défauts que présente, par rapport à la glace, le verre à vitre : sa planéité est beaucoup moins bonne et les rayons qu'il réfléchit sont parfois extrêmement dispersés. La difficulté était donc plus grande pour regrouper ces rayons par courbure imposée du réflecteur, que si ce dernier avait été constitué de véritable glace.

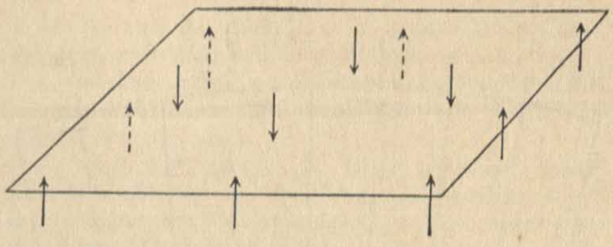

Fig. 10. Schéma de la déformation d'une glace plane par contrainte mécanique permanente ; les flèches centrales indiquent une poussée vers le bas, les flèches latérales une poussée vers le haut ; chaque poussée peut être réglée en fonction de la forme de l'image que donnent les rayons réfléchis par la glace.

Le schéma de réglage a été le suivant. Il s'agit de construire un certain nombre de couronnes réfléchissantes, chacune de ces couronnes étant constituée d'éléments réflecteurs identiques puisqu'ils peuvent se déduire les uns des autres par une rotation autour de l'axe du paraboloïde. Or, chacun des éléments de la figure 9, *a*, *a'*, ..., *b*, *b'*, ..., etc., présente déjà une trop grande surface pour qu'on puisse appliquer le principe décrit plus haut; il faut que chacun de ces éléments porte lui-même un certain nombre de glaces élémentaires, celles-ci étant disposées sur un support commun P (fig. 11) qui porte en même temps les dispositifs mécaniques permettant les courbures et les réglages. Chaque plaque P sera identique à ses voisines d'une même couronne, et il en sera de même pour toutes les glaces courbées qu'elle soutient.

La courbure de ces glaces ne sera pas réalisée sur le paraboloïde que schématise la figure 8 mais sur une demi-parabole portant, au niveau des cercles coaxiaux, les supports convenables.

Un rayonnement artificiel (fig. 12) ayant les caractéristiques du rayonnement solaire éclaire parallèlement à l'axe du paraboloïde les différentes plaques soumises au réglage. Le foyer F où se trouve un écran perpendiculaire à l'axe précédent est le foyer de la parabole schématisée approximativement par la trace des plans P_1, P_2, P_3, P_4, etc.

Une plaque étant placée sur son support, et éclairée par le rayonnement artificiel, on obture vingt-trois sur vingt-quatre des glaces élémentaires qu'elle soutient. La vingt-quatrième glace est courbée et orientée par des poussées avant et arrière que l'on règle progressivement, de manière à donner une tache lumineuse aussi réduite que possible au foyer F. Cette tache doit également se trouver, autant que possible, comprise

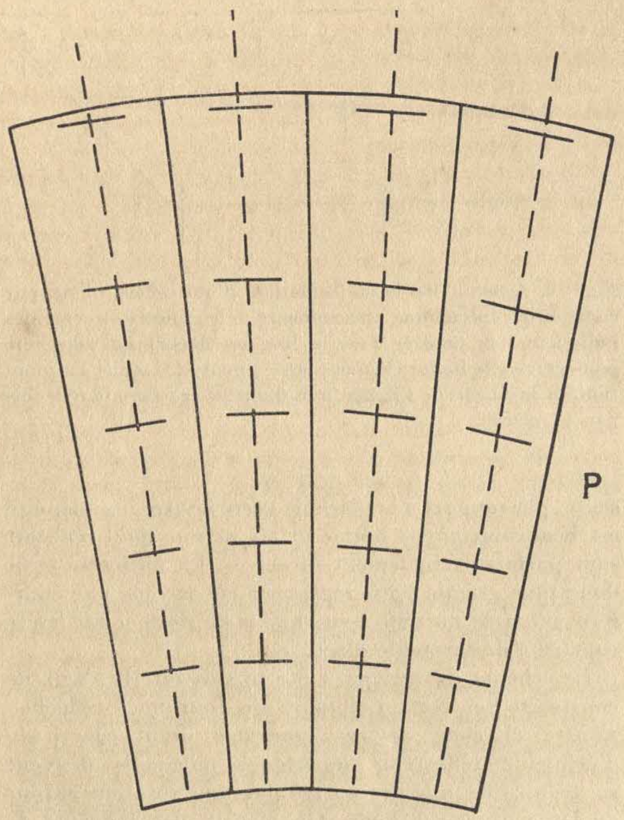

Fig. 11. Plaque support soutenant vingt-quatre glaces élémentaires et leurs éléments de courbure et d'orientation.

dans un cercle de diamètre déterminé dont le centre est situé sur l'axe de la parabole. Lorsque la vingt-quatrième glace est réglée, elle est obturée et on procède, pour toutes les autres glaces, découvertes une à une, à la mise en place des faisceaux qu'elles réfléchissent.

Lorsque tous les réglages d'une plaque sont terminés, l'enlèvement des écrans montre la qualité de la concentration globale obtenue.

Les plaques étant réglées, elles seront reportées, en une zone quelconque de leurs couronnes respectives, sur le paraboloïde. Cette disposition facilite beaucoup les réglages. Il y a, en effet, sur le paraboloïde de Mont-Louis, 3.500 glaces élémentaires, courbées par contrainte mécanique, alors qu'il y a seulement 146 plaques supports. C'est donc 146 réglages qui seront effectués sur le paraboloïde lui-même.

Indiquons aussi qu'un léger déplacement angulaire de la plaque ne change pas sensiblement la qualité de la focalisation qu'elle donne. On pourra donc régler l'image donnée par chaque plaque par déplacement de ses points d'appui sans diminuer la concentration énergétique au foyer.

Le problème s'est posé du réglage des faisceaux réfléchis par les différentes plaques, le foyer étant déjà soumis à un éclairement énergétique considérable. On pourrait évidemment obturer toutes les plaques sauf une, mais ce procédé est laborieux étant donné les dimensions de l'appareil.

Il a été plus simple, pour rectifier les réglages imparfaits de mettre au foyer une source lumineuse intense et quasi ponctuelle et d'observer, pendant la nuit, sur des écrans placés dans des positions et à des distances convenables, les profils de chacune des plaques réfléchissantes. A l'heure actuelle, l'appareil de Mont-Louis, dont la puissance maximum est de 75 kW et qui comporte trois mille cinq cents glaces élémentaires courbées, peut atteindre une température de 3.000° et donne des résultats équivalents à ceux que l'on obtiendrait par la superposition des taches lumineuses données par vingt-cinq mille glaces planes.

Il serait d'ailleurs probablement impossible, pour des appareils de très grandes dimensions, de ne pas mettre les glaces planes sous une certaine contrainte ; sinon elles seraient trop sensibles à toute pression éventuelle due, par exemple, au vent qui s'exercerait sur elles ; l'image au foyer oscillerait beaucoup alors que, sous contrainte, l'image des glaces reste parfaitement fixe.

L'extrapolation de telles machines doit être obtenue sans difficulté pour des puissances unitaires pouvant

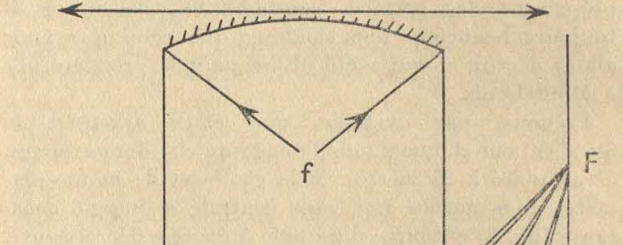

Fig. 12. Réglage des réflecteurs élémentaires sur leurs plaques supports.

atteindre plusieurs milliers de kilowatts. Les glaces élémentaires soumises à la courbure seraient alors de véritables glaces de dimensions classiques et leur nombre, plus important que dans l'appareil de Mont-Louis, serait défini par l'énergie totale qu'il serait nécessaire d'obtenir.

On voit donc que l'extrapolation du prototype de Mont-Louis doit conduire, sans aléa, à des unités, non seulement beaucoup plus puissantes, mais également d'une perfection optique notablement supérieure.

RÉCEPTION DE L'ÉNERGIE SOLAIRE PAR LES SUBSTANCES

Nous avons donné récemment, avec M. Foëx, les principales caractéristiques des techniques de chauffage par rayonnement [5]. On sait qu'une substance présente, pour chaque température, des facteurs déterminés de réflexion, d'absorption et de transmission vis-à-vis d'un rayonnement de longueur d'onde λ. Ces facteurs sont assez variables avec la température, mais dépendent surtout de la longueur d'onde. Nous avons l'habitude d'apprécier, avec notre seul contrôle visuel, le comportement des corps soumis à l'action de la lumière naturelle, c'est-à-dire, aux absorptions atmosphériques près, à l'action de la lumière solaire. Il y a des corps réflecteurs, comme les métaux polis, des corps absorbants, qui nous paraissent très sombres, et des corps transparents, au travers desquels nous pouvons voir. Cette classification grossière est rendue plus précise et quantitative grâce à l'emploi de différents types de récepteurs d'énergie pouvant explorer un large domaine de longueurs d'onde.

Les résultats obtenus, bien qu'encore insuffisamment développés, surtout dans le domaine des températures élevées, sont d'une grande importance pour l'utilisation de l'énergie solaire qu'il importe avant tout d'absorber avec le minimum de pertes par transmission et par réflexion.

Les techniques de réception du rayonnement solaire seront étroitement liées aux caractères précédents (réflexion, absorption, transmission) que présentent les substances. D'autres facteurs, d'ordre thermique, comme leur chaleur spécifique et, surtout, leur conductibilité calorifique, interviendront.

La réception directe de l'énergie solaire, c'est-à-dire la concentration du rayonnement sur une surface plane constituée par la matière à traiter, pourra s'effectuer, avec de bons rendements, si la substance possède des facteurs de réflexion et de transmission suffisamment faibles, et un facteur d'absorption important. Si la substance à l'état compact ne présente pas ces caractéristiques, on peut y remédier en la traitant sous forme divisée, ce qui a pour effet de bloquer une notable proportion d'énergie sous forme de réflexions successives dans la masse du produit. Tout se passe comme si les facteurs de réflexion et de transmission étaient diminués et le facteur d'absorption augmenté.

La matière divisée présente aussi une conductibilité calorifique beaucoup plus faible que celle qu'elle possède à l'état compact.

Le traitement direct par le rayonnement solaire permet d'effectuer des opérations très variées jusqu'à des températures dépassant 3.000°, et ceci en l'absence de creuset. La matière repose en effet sur elle-même et il se crée, entre le récipient qui la contient et la zone dans laquelle elle est chauffée, un gradient de température considérable. Ce gradient existe aussi entre la surface proprement dite et les zones sous-jacentes. On peut avoir, par exemple, sur un produit fondu sous une épaisseur assez notable, une augmentation superficielle de température provoquant de fortes volatilisations. On a intérêt, pour éviter cet inconvénient, à renouveler constamment, par un apport de matière, la surface chauffée, ou encore à faire défiler le produit au niveau du foyer (fig. 13). On obtient ainsi de longs échantillons fondus ou frittés.

Bien entendu, de telles opérations peuvent être effectuées à l'air, mais aussi bien sous un vitrage transparent, dans des atmosphères conditionnées.

Le traitement direct donne parfois de mauvais rendements, soit que la substance réfléchisse, soit qu'elle transmette le rayonnement. Par exemple, il devient impossible, malgré la grande densité d'énergie, de fondre dans l'hydrogène du fer pur, car le métal présente dans ces conditions un grand facteur de réflexion par rapport aux différents λ du rayonnement solaire.

Par contre, ce même fer est très aisément fondu à l'air, car il se recouvre d'une pellicule d'oxyde dont le facteur d'absorption est très élevé, de l'ordre de celui du carbone, et voisin de celui du corps noir (on sait que le facteur d'absorption du corps noir est, par définition, égal à l'unité).

On voit donc combien, dans le cas des traitements directs, le rôle de l'atmosphère en contact avec les substances peut avoir d'importance pour la réception du rayonnement solaire.

Un autre procédé, qui s'est avéré très fructueux pour le traitement des substances ultra-réfractaires et les métaux, consiste à recevoir l'énergie solaire par un orifice de faible diamètre pratiqué dans une cavité calorifugée (fig. 14) constituée par la substance elle-même. De très nombreuses variantes de ces appareils : fours fixes, fours tournants à vitesse lente, fours tournants à vitesse rapide, ont permis des opérations de types extrêmement variés, soit dans l'air, soit en atmosphères conditionnées.

Le chauffage dans des cavités calorifugées permet d'une part d'éviter le choc thermique obtenu au foyer, d'autre part de traiter, avec de bons rendements, les substances à grand facteur de réflexion et, en outre, d'obtenir simultanément des quantités importantes de matière.

On fait couramment, au laboratoire de l'énergie

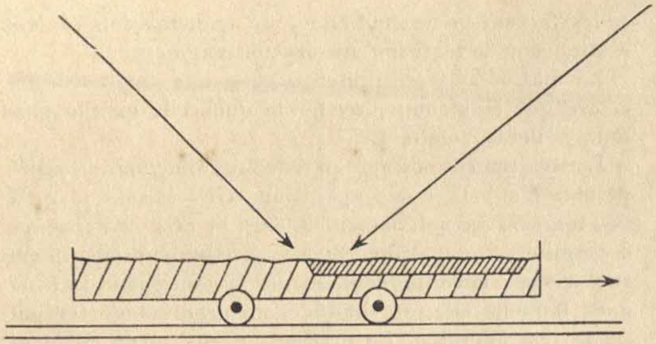

Fig. 13. Fusion directe en gouttière.

solaire de Mont-Louis, à l'aide de fours tournants à vitesse rapide, des fusions ou des frittages de corps ultra-réfractaires à raison de 30 kg à la fois, et des fusions de fer ou d'alliages à raison de 100 kg à la fois.

Il semble que les machines solaires soient déjà suffisamment au point pour permettre d'aborder de nombreux types d'opérations aboutissant à la production de matières utilisables et, en particulier, de produits purs. Le développement des techniques de construction de ces machines apporte constamment des diminutions substantielles de leur prix de revient. On peut avoir la certitude que la première fabrication en série de fours solaires donnera encore de nouvelles possibilités d'extension de leur domaine de rentabilité.

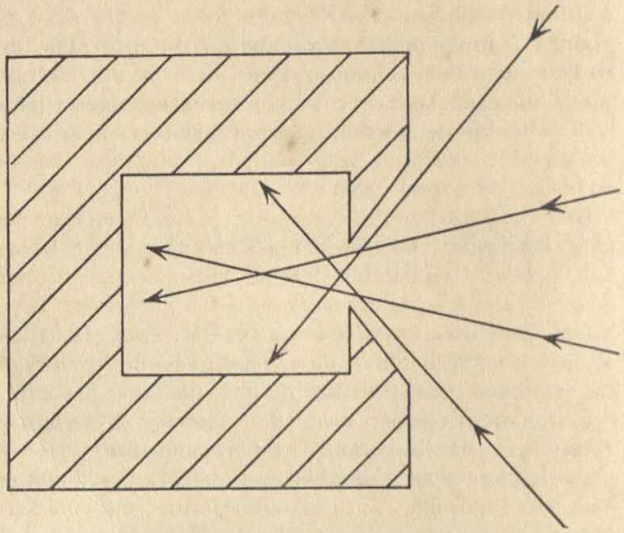

Fig. 14. Principe de l'accumulation de l'énergie solaire dans une cavité calorifugée (corps noir).

STRUCTURE OF SOLAR ENERGY UNITS

by

F. TROMBE

SUMMARY

The energy-output curve of the sun's radiations in function of their wavelength has its peak at about 0.47 microns and is comparable to the theoretical curve for the radiations of a black body raised to 6,200° absolute.

We can therefore take it that the energy radiated at the sun's surface is about 8 kw. per cm.^{2}. At the earth's surface, though the energy content of the sun's rays is much diminished (1 kw. per m.^{2}), their spectroscopic pattern remains pretty much the same.

Fixed aspect solar energy collectors always operate on the "glass-house" principle, using sheets of glass through which the sun's rays can pass but which retain the long waves radiated by the heat-absorbing surface.

This type of collector gives maximum temperatures of over 100° and working temperatures for practical use of 60°-75°.

A disadvantage is the variation of the area heat-absorbing surface exposed to the sun in the course of the day which causes a corresponding variation in the amount of energy collected.

For a number of uses, notably power generation, and high temperature operations, either the collector itself must be kept constantly trained on the sun or the sun's rays must be deflected by an adjustable plane mirror on to a fixed collector.

The author discusses the considerations affecting the focused deflection of sunlight and recommends the use of silver-backed glass with the silvering protected by an electrolytic deposit of copper.

Then follows a description of an experimental unit collecting sufficient solar energy for a power yield of about 75 kw. It consists of (a) a reflector 135 m.^{2} in area consisting of five hundred and forty 50 × 50 cm. plane mirrors, kept in automatic alignment by shifts in the incidence of the reflected light ray actuating photo-electric cells; (b) a 90 m.^{2} parabolic mirror collecting the light from the reflector.

With regard to the degree of optical concentration by the reflector the author explains the state in which the concentrated sunlight reaches the collecting surface of a parabolic cylinder mirror and a revolving paraboloid and goes on to discuss the possibilities of constructing paraboloids of large dimensions by the use of the various types of reflecting surface.

The methods which made the building of the Mont-Louis unit possible were: (a) The concentration on a single collector of the rays from a large number of separate reflectors (Buffon process); (b) giving a permanent warp to each of the mirrors in the collector to reduce the size of the beams thrown by them on to the heat absorbing surface.

The 3,500 stressed mirrors at Mont-Louis give the same concentration of energy as would be obtainable by superimposing the beams from 25,000 plane mirrors.

The scale of the apparatus described above can be increased without much difficulty to dimensions yielding usable quantities of energy.

A description is given of the alternative ways of using the solar radiation concentrated at the forms of the paraboloid; it can either be applied direct—which calls for specific optical characteristics in the substances treated; or it can be directed into insulated cavities forming "black bodies" in which substances can be treated in large quantities without "thermal shock" and without loss of energy by reflexion or transmission.

The indications are that large scale solar energy units are already sufficiently developed for their use to be a commercial proposition for a number of high temperature processes, notably refining of various types.

ESTRUCTURA DE LAS MÁQUINAS QUE UTILIZAN LA ENERGÍA SOLAR

por

F. Trombe

RESUMEN

La radiación solar se caracteriza por una curva de emisión energética en función de la longitud de onda cuyo máximo es de 0,47 micrones. Esa curva es bastante parecida a la que se obtendría con la radiación de un cuerpo negro a 6.200° de temperatura.

De ello resulta que la superficie del sol irradia unos 8 kW por cm^2. Al nivel de la tierra, esa radiación, a pesar de hallarse muy dispersa (1 kW por m^2), conserva sensiblemente sus caracteres espectrales.

La recepción de los rayos solares con aparatos fijos se efectúa siempre según el "efecto de invernadero" que consiste en bloquear las radiaciones de las grandes longitudes de onda de los cuerpos calentados por la radiación solar mediante la interposición de unas vidrieras que dejan pasar dicha radiación.

Ese dispositivo ofrece la posibilidad de alcanzar temperaturas máximas que excedan los 100° C y temperaturas de funcionamiento de los aparatos receptores de unos 60 a 75°.

Los aparatos fijos tienen el inconveniente de ofrecer perpendicularmente a la dirección del sol superficies aparentes extremadamente variables en el curso del día, por lo que la energía que reciben es también muy variable.

Para diferentes utilizaciones, sobre todo para la producción de fuerza motriz y de altas temperaturas, es necesario orientar constantemente el aparato receptor hacia el sol u orientar la irradiación solar por medio de un espejo plano dirigido hacia el aparato receptor fijo.

El autor estudia las condiciones de reflexión y de

orientación de la radiación solar y preconiza el empleo de cristal azogado por la cara posterior, protegiendo el azogue con una capa de cobre depositado por electrólisis.

Luego se describe una instalación prototipo que permite orientar y concentrar una cantidad de energía solar suficiente para conseguir una potencia de 75 kW. El aparato se compone: de un orientador de 135 m², constituído por 540 espejos planos de 50 × 50 cm (es orientador se guía mediante unas células fotoeléctricas que controlan la dirección de la radiación reflejada); de un espejo parabólico de 90 m² que recibe la radiación procedente del orientador.

A propósito de la concentración óptica del orientador, el autor precisa las condiciones de recepción de la energía solar concentrada en el foco de un espejo cilindroparabólico o de un paraboloide de revolución. El autor examina después las posibilidades de realización de grandes paraboloides por medio de las diferentes superficies reflectoras.

El procedimiento que ha permitido la construcción del aparato de Mont-Louis consiste:

1. En acumular sobre una misma superficie receptora los rayos solares procedentes de numerosos reflectores individuales (procedimiento de Buffon).
2. En someter a una presión permanente cada uno de los espejos receptores a fin de disminuir las dimensiones que dan en el plano receptor.

Los 3.500 espejos curvos de Mont-Louis dan una concentración de energía idéntica a la que se obtendría con la superposición de las manchas luminosas producidas por 25.000 espejos planos.

Los aparatos descritos más arriba pueden extrapolarse con facilidad a dimensiones que permitan la utilización industrial de la energía solar.

El autor describe las condiciones en las que puede recibirse la radiación solar concentrada en el foco del paraboloide: recepción en la superficie que requiere caracteres ópticos de substancias bien determinadas, o recepción en cavidades calorífugas o "cuerpo negro" que permitan tratar substancias en gran cantidad a la vez, sin choque térmico y sin pérdida de energía por reflexión o transmisión.

Parece que las grandes máquinas solares están ya suficientemente perfeccionadas para poder abordar, de una manera rentable, diferentes tratamientos a temperaturas elevadas, y en particular los que se utilizan para la obtención de productos puros.

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DISCUSSION

M. BAUM. Les recherches du professeur F. Trombe et de ses collaborateurs dans le domaine de la production de hautes températures sont très intéressantes. Son grand miroir parabolique, à en juger par les températures produites, présente un degré assez élevé de perfection. Pour déterminer exactement ce degré, il serait utile d'étudier l'inégalité de la répartition de l'énergie sur le plan focal.

Une telle inégalité existe toujours, quel que soit le degré de perfection du miroir parabolique. Il suffit pour s'en convaincre d'examiner la figure 1.

Les images du soleil projetées au foyer par les parties centrales du miroir ont des dimensions moindres que celles qui sont projetées par les bords du miroir. En raison de la superposition de ces images, la surface focale présente donc une chaleur plus intense dans sa partie centrale que dans sa partie périphérique.

Pour un miroir idéal absolument parfait, le diamètre de la surface focale, comme il résulte de constructions géométriques simples, peut être déterminé au moyen de la formule :

$$d = \mathrm{D}\,\mathrm{ctg}\,\frac{\alpha}{2}\,\mathrm{tg}\left(\frac{\alpha}{2} + \frac{\varepsilon^{♀}}{2}\right)$$

où $\varepsilon^{♀}$ = le diamètre angulaire du soleil.

Pour un miroir réel, $\varepsilon^{♀}$ représente une grandeur qui mesure aussi la "dispersion" des rayons, due à l'imperfection du miroir.

Par sa forme, la courbe de la répartition de l'intensité thermique sur le plan de la surface focale (fig. 2) rappelle la courbe des erreurs de Gauss.

Dans notre laboratoire, nous avons établi, pour construire ces courbes. des formules théoriques dont nos recherches expérimentales ont confirmé l'exactitude.

Des expériences ont été faites avec des miroirs paraboliques parfaits et imparfaits, avec des miroirs en forme de cylindres paraboliques, et avec des systèmes constitués par des groupes de miroirs.

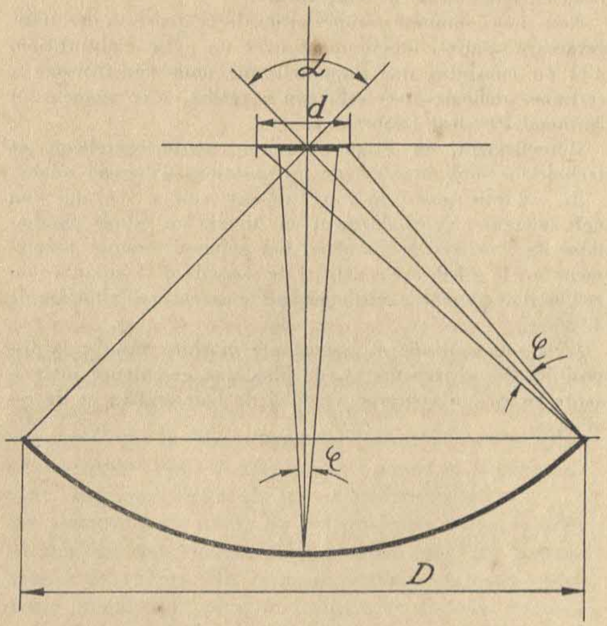
Nous avons mis au point plusieurs procédés de recherche :

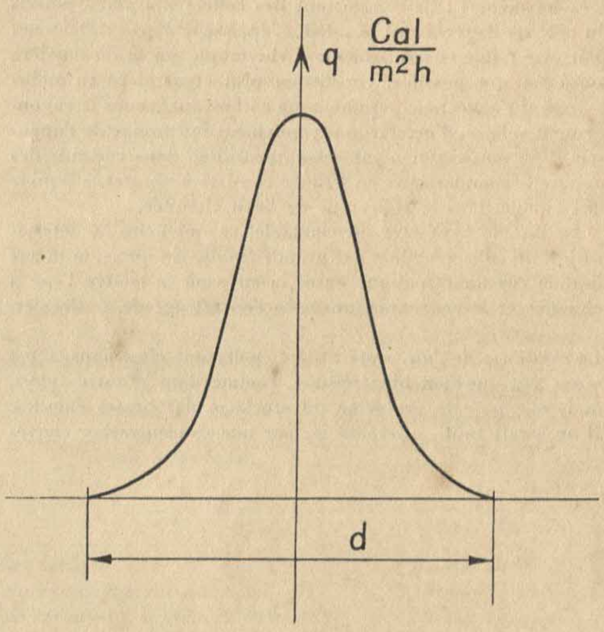
1. Un procédé calorimétrique permettant de mesurer l'intensité des rayons du soleil;

2. Un procédé photométrique permettant de mesurer l'intensité des rayons de la lune ;
3. Un procédé consistant à photographier sur le plan focal l'image de la lune et à mesurer la luminosité d'après le cliché.

M. Trombe. Je réponds au professeur Baum. Nous avons fait avec le grand four solaire de Mont-Louis des expériences de répartition d'énergie sur la tache focale en utilisant des récepteurs en fer soudé pleins ou percés de trous de différents diamètres. Ces récepteurs sont refroidis par un courant d'eau dont la température et le débit sont mesurés.

On retrouve, pour la représentation de l'énergie, une courbe qui rappelle celle de la figure 5 de mon rapport, avec un étalement latéral évidemment plus grand et une légère variation dans la partie centrale (figure en plat dans la courbe théorique).





ANNEXE : ALLOCUTION PRONONCÉE PAR M. TROMBE

Monsieur le président, Mesdames, Messieurs,

Ma communication ayant trait, seulement, aux fours solaires, je pense qu'il est utile de vous renseigner sur les autres domaines de notre activité.

Je désirerais donc donner quelques précisions relatives aux recherches effectuées en France sur l'énergie solaire.

La plus grande partie de ces recherches sont faites sous l'égide de notre Centre national de la recherche scientifique.

L'énergie solaire, comme vous le savez, est une énergie à haut potentiel thermodynamique. Elle pourrait, de ce fait, être transformée, avec un bon rendement, en toute autre forme d'énergie (énergie mécanique, énergie électrique) si nous disposions, pour cela, d'un cycle thermique d'amplitude convenable. Or, pour les petits appareils moteurs, on peut avoir des rendements pratiques de 3 à 8 % et pour les grands de 20 à 25 %.

Si l'énergie solaire est, comme l'on dit, "compétitive" avec les autres formes d'énergie, lorsqu'on regarde seulement l'équivalent énergétique en calories, elle ne l'est plus dans le cas des moteurs. Ils sont encore beaucoup trop chers.

On poursuit, en France, au CNRS, dans mon laboratoire et en collaboration avec la direction de Bellevue, des recherches dans ce sens : améliorer les rendements des moteurs et abaisser le prix de revient des machines solaires permettant d'avoir une source chaude en équilibre à 800-900° C. et fonctionnant pratiquement à 400 ou 500° C. lorsqu'on lui demande de fournir des calories avec un bon rendement.

Pour l'instant, je suis d'accord avec MM. Golding et Thacker qui assignent à l'énergie solaire, dans leur plan de répartition, un seul rôle : celui de fournir des calories.

A ce sujet, je voudrais dire que j'ai été frappé du développement des mesures concernant le vent. Il n'en existe certainement pas d'équivalent pour les mesures de l'énergie solaire, et cela restreint beaucoup la valeur des bilans que l'on peut établir.

Les bilans météorologiques mentionnent bien la présence du rayonnement solaire. Or, c'est le produit : heures de présence × énergie par unité de surface qui nous intéresse pour chaque jour de l'année.

L'Unesco pourrait peut-être provoquer un tel inventaire du rayonnement du soleil dans les différents pays. C'est une question qui pourrait être posée.

Pour en revenir à notre activité, je mentionnerai que nous nous sommes occupés, en dehors des fours solaires, des questions suivantes :

Le chauffage de l'eau. Il nous est apparu, il y a quelques années, que la recherche fondamentale, dans ce domaine, semblait avoir fourni toutes les données nécessaires. On sait faire des appareils simples à très haut rendement, et ceci dans plusieurs pays.

Le problème est d'ordre technologique. Il faut que la machine dure longtemps, résiste aux conditions climatiques extrêmes du lieu et soit d'un entretien facile. Il y a plusieurs bonnes solutions qui sont déjà utilisées en France au stade commercial.

Les caractéristiques de ces appareils sont toujours à peu près les mêmes : ils comportent des collecteurs plats, noircis du côté où ils reçoivent le soleil. L'épaisseur de ces collecteurs doit être faible et leur isolement thermique sur la face arrière aussi bon que possible. Un vitrage protecteur placé au moins à 1 cm du collecteur permet, tout en laissant passer le rayonnement solaire, d'arrêter le rayonnement infrarouge de l'appareil. Une amélioration intéressante utilisée dans certains des appareils commerciaux en France consiste à séparer le liquide qui circule dans le collecteur de l'eau chauffée.

Le liquide peut être incongelable, ce qui évite la détérioration du collecteur lors des grands froids. En outre, le même liquide circulant toujours entre la cuve où se trouve l'eau à chauffer et le collecteur, on évite l'entartrage de ce dernier.

Le chauffage de l'air a été étudié également chez nous. C'est aussi une question bien résolue, comme dans d'autres pays, mais elle pose le problème du stockage des basses calories. Il en serait tout utrement si, par une concentration convenable du rayonnement, la température de l'accumulateur pouvait être suffisamment élevée.

De même pour la distillation de l'eau, nous retrouvons comme Harding, Maurain et Maria Talkes, des rendements compris entre 5 et 6 litres par mètre carré d'insolateurs et par jour ; le rendement est d'autant plus élevé que la température de la zone de condensation est plus grande. Ceci résulte de l'allure de la courbe représentant la tension de vapeur de l'eau en fonction de la température.

Nous nous sommes occupés enfin de la question des réfrigérateurs solaires, fonctionnant avec un cycle d'absorption. J'ai pu constater que l'appareil que nous construisons a certaines analogies avec celui qui se réalise en ce moment au National Physical Laboratory.

Actuellement, en France, environ trente chercheurs et techniciens sont orientés sur ces questions d'énergie solaire.

Je voudrais également vous rappeler (voir p. 166) que l'on doit inaugurer prochainement en Algérie un miroir parabolique de 8 mètres de diamètre. Cet appareil, braqué directement sur le soleil, est constitué de secteurs d'aluminium poli et l'on doit obtenir à son foyer une température de l'ordre de 3.000° C.

C'est une nouvelle et importante machine mise à la disposition des chercheurs et, de plus, une expérience intéressante en ce qui concerne l'emploi de l'aluminium et de ses alliages.

DU MOYEN DE CAPTER LA CHALEUR SOLAIRE

par

H. MASSON

La création à Dakar d'un Laboratoire de recherches sur l'utilisation de l'énergie solaire est toute récente. En réalité les expériences avaient commencé il y a deux ans sur l'initiative du regretté André Nizery, avec l'appui de la Société d'économie mixte "Energie des mers" et du gouvernement général de l'A.-O.F. Le but proposé était de rechercher un moyen de réchauffer de l'eau sous l'effet de la radiation solaire.

Je voudrais, au cours de ces quelques pages, parler d'abord des expériences préliminaires qui ont permis d'établir la théorie du procédé, ensuite exposer cette théorie en faisant ressortir d'après les données mathématiques du problème les limites de la méthode ; enfin, montrer comment, en se rapprochant des conditions théoriques, on peut augmenter simultanément, dans les limites prévues, la température, la quantité de chaleur captée et le rendement du système. Il est nécessaire de distinguer ces trois éléments car le problème présente un double aspect : on peut en effet se proposer de porter l'eau qui a traversé l'insolateur à une température maximum durant un temps minimum, mais on peut aussi, travaillant à des températures données, d'entrée et de sortie, s'efforcer d'obtenir un rendement maximum.

EXPÉRIENCES PRÉLIMINAIRES

Les premières expériences furent très simples. Si l'on admet que les pertes principales de chaleur dans l'échauffement de l'eau sont dues à l'évaporation, il importait d'empêcher cette évaporation. Dans des petits bassins de ciment de 1 m^2 de surface environ et de 0,40 m de profondeur, l'eau était exposée durant une journée à la radiation solaire Q_0 mesurée avec un solarimètre Gorczinski. On peut adopter comme valeur moyenne de la radiation globale journalière durant les expériences 600 cal/cm^2.

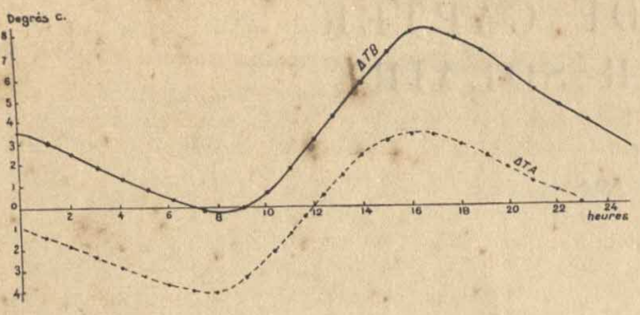
Dans l'un des bassins l'eau était en contact avec l'air. Dans les autres elle était recouverte de différentes substances. Les températures étaient mesurées à 16 heures avec un thermomètre à mercure placé dans la couche supérieure de l'eau à 2 cm environ de la surface. Voici les résultats :

Système protecteur	*Elévation de température en centièmes de degré par calorie incidente* $K = \frac{\Delta t \times 100}{Q_0}$
Eau seule	1,07 sur 67 exp.
Eau recouverte de mazout	1,19 sur 57 exp,
Eau recouverte d'huile de vaseline	1,20 sur 43 exp.
Eau recouverte d'un châssis vitré et d'huile	1,37 sur 12 exp.
Eau recouverte d'un châssis vitré et de mazout	1,70 sur 20 exp.

Ces chiffres ne pouvaient être qu'indicatifs car l'échauffement de l'eau immobile ne présente guère d'intérêt pratique. Une deuxième série d'expériences a concerné l'eau courante.

EXPÉRIENCES EN EAU COURANTE

L'eau s'écoulait dans deux bassins en ciment de 30 mètres de long et 5 mètres de large, avec un débit constant de 1,75 m^3 à l'heure sur une profondeur de 30 cm. Un dispositif de rampe d'arrivée et de reprise de l'eau assurait un brassage convenable. L'un des bassins, A, servait de témoin. Dans l'autre, B, l'eau fut d'abord recouverte d'un film d'huile de vaseline destiné à diminuer et pratiquement à supprimer les pertes de chaleur dues à l'évaporation. Mais l'huile se salit rapidement et devient moins perméable aux radiations solaires. De plus le prix de revient du procédé est élevé. J'ai alors utilisé le mazout, beaucoup moins coûteux. Mais le mazout s'évapore et devient opaque. Il faut le changer tous les vingt jours, deux fois plus souvent que l'huile. De plus, l'alizé souvent violent est fréquent dans nos



——— Eau recouverte d'huile.
- - - - Eau exposée directement au soleil.

Fig. 1. Élévation de température de l'eau durant son trajet dans les bassins (10 juin 1951).

régions durant la saison froide ; il accumulait le liquide protecteur contre une paroi du bassin et le reste de la surface libre était alors soumis à l'évaporation. Pour remédier à cet inconvénient, j'ai disposé à la surface du bassin B un quadrillage découpant sur l'eau des surfaces de 1 m² environ. Ce procédé s'est révélé satisfaisant.

Avant de passer aux résultats, il nous faut définir soigneusement les termes qui seront employés. J'appellerai E_p, (efficacité positive) le nombre de calories gagnées durant la période d'insolation, et E_t (efficacité totale) le nombre de calories gagnées en vingt-quatre heures. E_p et E_t sont donc des différences calculées d'après les températures et les débits (identiques) entre le bassin protégé et le bassin témoin. De même je désignerai l'élévation de température moyenne de l'eau des deux bassins pour la durée de l'insolation et pour une période de vingt-quatre heures par Δt_p et Δt_t respectivement. Enfin Δt_x sera l'élévation de température maximum ; Δt_p, Δt_t, et Δt_x sont calculés comme E_p et E_t par différence.

On aura :

$$E_p = \Delta t_p \times D \times 10^6 \times H$$

$$E_t = \Delta t_t \times D \times 10^6 \times 24$$

(H étant en heures la durée de l'insolation ; dans les deux cas, D est le débit exprimé en m³/h).

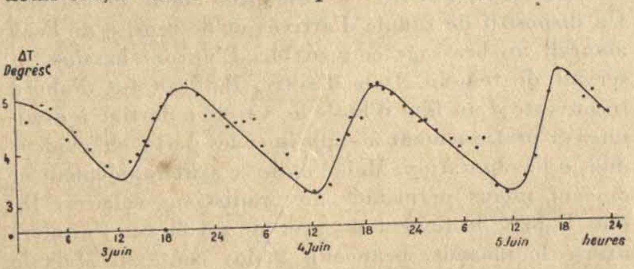


Fig. 2. Différence de température de l'eau de sortie des bassins A et B. Cas de l'huile.

Ceci nous amène à la définition des rendements :

$$\rho_p = \frac{E_p}{Q_0 \times S} \qquad \rho_t = \frac{E_t}{Q_0 \times S}$$

(Q_0 est la radiation globale exprimée en calories par cm² et S la surface des bassins en cm².)

La température initiale de l'eau est sensiblement constante (30°). Les graphiques 1 et 2 donnent l'allure des courbes dans le cas de l'huile. Le graphique 1 correspond à l'échauffement de l'eau protégée et de l'eau non protégée. Il permet le calcul de Δt_p et de E_p par mesure de la surface comprise entre la courbe en trait plein et l'axe des temps du côté des températures positives. De même le graphique 2 permet le calcul de Δt_t et de E_t ; les graphiques 3 et 4 sont relatifs à la variation de température due au mazout.

Les résultats relatifs à des moyennes correspondant à une durée de un mois (douze expériences retenues par jour de beau temps) figurent dans le premier tableau p. 177.

D'autres expériences ont été entreprises sur des bassins moins larges (30 m de long et 1 m de large). Cette fois on a comparé l'eau recouverte de mazout seul, et l'eau recouverte de verre et de mazout. La profondeur était restée la même mais le débit était de 0,9 m³. Avec ce débit la distance de 30 mètres est approximativement parcourue pendant la durée de l'insolation. (Voir deuxième tableau, p. 177.)

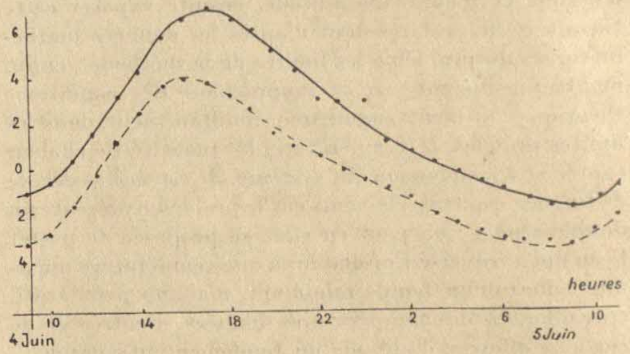


Fig. 3. Élévation de température de l'eau recouverte de mazout.

Grand bassin 150 m³. Débit 1,75 m³/h.
Petit bassin 30 m³. Débit 0,9 m³/h.

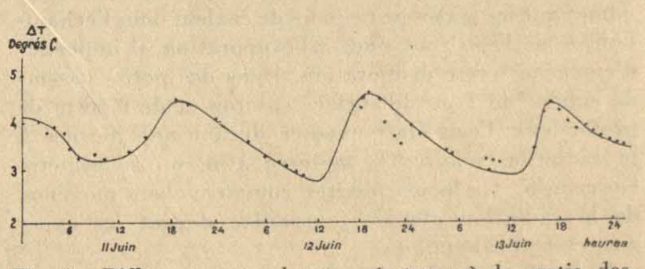


Fig. 4. Différence entre les températures à la sortie des grands bassins de l'eau recouverte de mazout et de l'eau non protégée. Expériences de 1951. (Mazout seul.)

	Δt_x	Δt_p	Δt_t	E_p	E_t	ρ_p	ρ_t
Huile de vaseline	8,0	4,4	4	77×10^6	168×10^6	0,08	0,16
Mazout	6,2	3,8	3,5	$66,5 \times 10^6$	147×10^6	0,07	0,14

	Δt_x	Δt_p	Δt_t	E_p	E_t	ρ_p	ρ_t
Mazout seul	2,8	2,0	1,1	18×10^6	24×10^6	0,09	0,11
Mazout recouvert de verre	3,7	2,2	5	$19,8 \times 10^6$	108×10^6	0,13	0,60

De ces expériences on pouvait principalement déduire que le mazout recouvert d'une vitre se révèle le meilleur procédé, surtout si l'on considère l'efficacité totale et le rendement total qui tiennent compte du refroidissement nocturne. Le verre en effet s'oppose aux radiations calorifiques de grande longueur d'onde.

Ces données expérimentales ont été le point de départ d'une étude mathématique qui a permis une amélioration systématique du procédé.

CONSIDÉRATIONS THÉORIQUES ÉLÉMENTAIRES

Revenons au bassin précédemment décrit. Sa longueur est x, sa largeur est l, l'eau qui y circule a une profondeur h. Elle est recouverte d'un film protecteur liquide (huile ou mazout) ou d'un solide (tôle) d'épaisseur ε, petite dans tous les cas, de l'ordre de 1 mm par exemple.

Pour fixer les idées, considérons le cas où l'eau est recouverte d'un film de mazout.

Nous supposerons, pour simplifier, que la radiation solaire arrive perpendiculairement à la surface de liquide dont la couche protectrice prend la température t_m, la température initiale de l'eau étant t_i. Soit λ le coefficient de transmission de la couche protectrice, dont nous préciserons la définition de la manière suivante :

"Quantité de chaleur effectivement transmise à l'eau durant une seconde par chaque centimètre carré de la couche protectrice dont les parois ont entre elles une différence de température de 1° C."

On voit que λ comprend en réalité trois termes : la conductibilité interne du mazout et la conductibilité superficielle air-mazout et mazout-eau.

LA TEMPÉRATURE DE L'EAU

Un élément de surface ldx à la température instantanée t reçoit donc par seconde une quantité de chaleur $\lambda(t_m - t)ldx$. Cette quantité de chaleur a échauffé de d_t° un volume d'eau lhv.

On peut donc écrire

$$\lambda(t_m - t)ldx = hlvdt \quad \text{ou} \quad \frac{\lambda dx}{hv} = \frac{dt}{t_m - t}.$$

Dans le second membre ne figurent ni la chaleur spécifique, ni la masse spécifique de l'eau que nous prendrons égales à 1.

Si on intègre de 0 à x en tenant compte de la température initiale t_i de l'eau, on obtient :

$$\frac{t_m - t_i}{t_m - t} = e^{\frac{\lambda x}{hv}}$$

(t étant la température de l'eau qui a parcouru la distance x dans le bassin).

On peut donc calculer

$$t = (t_i - t_m)\, e^{-\frac{\lambda x}{hv}} + t_m$$

et l'élévation de température de l'eau

$$\Delta t = (t - t_i) = (t_m - t_i) \left(1 - e^{-\frac{\lambda x}{hv}}\right.$$

LES PERTES

Toute la chaleur arrivant sur la couche protectrice ne sera pas transmise à l'eau. Une partie produira une évaporation du liquide. Cette évaporation est négligeable dans le cas de l'huile et *a fortiori* de la tôle (elle ne l'est pas dans le cas du mazout dont l'épaisseur varie avec le temps ; ce vieillissement du mazout est d'ailleurs un des principaux inconvénients de son emploi ; il faudrait en effet renouveler le film protecteur tous les vingt jours environ).

En conséquence, nous supposerons que la chaleur perdue par évaporation est nulle et nous n'en parlerons plus dans la suite ; la surface de l'eau n'étant pas en contact direct avec l'extérieur, nous admettrons qu'il n'y a aucune perte par la surface. Par contre une partie de la chaleur transmise à l'eau par la surface sera rayonnée par la paroi et ne servira pas à élever sa température. Appelons C_p la quantité de chaleur perdue par unité de surface de paroi durant l'unité de temps quand la différence de température entre l'eau et la paroi est de 1°. La quantité de chaleur perdue par la paroi est $C_p(t - t_p)$ par unité de temps. Nous supposons que la couche superficielle de l'eau est à la température t_m du film protecteur. Enfin nous admettons la loi de Newton pour le rayonnement.

En conséquence, toutes les pertes seront considérées comme proportionnelles aux différences de température et nous réunirons en un seul terme les pertes par conduction, convection et rayonnement.

A l'équilibre on aura :

Chaleur transmise à l'eau		Chaleur utilisée pour chauffer l'eau		Perte par les parois
$\lambda(t_m - t_i)$	$=$	Q	$+$	$C_p(t - t_p)$

En remplaçant t par sa valeur, on pourrait écrire :

$$\lambda(t_m - t_i) = Q + C_p[(t_i - t_m)e^{-\frac{\lambda x}{hv}} + (t_m - t_p)].$$

Si $t_i = t_m$ la température du film est à la température initiale de l'eau : le signe de Q dépend du signe et de la valeur de $t_m - t_p$.

Si $t_m < t_i$, l'eau réchauffe le film d'huile (la nuit par exemple).

Ce cas n'est pas intéressant dans le problème qui nous occupe : pour que le bilan calorifique se traduise par un gain de calories pour l'eau, il faudrait que le terme $C_p(t_m - t_p)$ soit négatif et de valeur absolue suffisamment élevée, ce qui est peu probable.

Si $t_m > t_i$, il est possible que pour une température suffisamment élevée de parois on ait :

$$C_p[(t_i - t_m)e^{-\frac{\lambda x}{hv}} + (t_m - t_p)] < 0$$

C_p est $\neq 0$ et positif.

Dans le cas d'une insolation moyenne on a $t_p > t_i$, mais $t_p < t_m$. Donc $t_m > t_p > t_i$, c'est-à-dire que la température des parois est supérieure à la température initiale de l'eau, mais inférieure à la température du liquide exposé à l'insolation.

L'inégalité

$$(t_i - t_m)e^{-\frac{\lambda x}{hv}} < t_p - t_m$$

peut s'écrire si l'on rend les deux nombres positifs :

$$(t_m - t_i)e^{-\frac{\lambda x}{hv}} > t_m - t_p.$$

Donc pour

$$x < \frac{hv}{\lambda} \operatorname{Log} \frac{t_m - t_i}{t_m - t_p},$$

il ne convient pas de calorifuger.

Dans le cas envisagé, la fraction $\frac{t_m - t_i}{t_m - t_p}$ est > 1 et le second membre est positif. Il est évident que si l'on avait $t_m > t_i > t_p$ la condition posée ne serait jamais réalisée et il faudrait toujours calorifuger.

Enfin l'inégalité précédente peut s'écrire

$$x < \frac{D}{\lambda l} \operatorname{Log} \frac{t_m - t_i}{t_m - t_p}.$$

Pour fixer les idées, supposons

$$\frac{t_m - t_i}{t_m - t_p} = 2$$

dans les bassins précédemment décrits avec $D = 1$ m³/h, $l = 1$ m et λ environ $\frac{2}{10^4}$ C.G.S. On aurait $x < 96$ m tandis que dans les échangeurs en tôle, pour un débit de 72 litres à l'heure, en donnant la même valeur à λ et au rapport de température, on trouverait $x < 7$ m.

Dans ce qui va suivre, nous supposerons un insolateur idéal dans lequel les pertes sont nulles. Nous allons maintenant passer en revue les différents facteurs qui interviennent pour donner à l'eau une température plus élevée et assurer un meilleur rendement.

LES DIFFÉRENTS FACTEURS QUI ENTRENT EN JEU

Nous distinguerons deux sortes de facteurs, qui influent sur le but proposé. D'abord ceux qui résultent du milieu, puis ceux qui sont liés à l'appareil lui-même.

Facteurs résultant du milieu.

1. L'intensité de la radiation solaire : la source de chaleur étant la radiation solaire, il importe de connaître la radiation globale et les heures d'insolation. Toutes les études ont été faites à Dakar près de la mer (à 14° 43' de latitude N., 17° 26' de longitude O.), où l'on peut compter en moyenne dix heures d'insolation par jour. Le ciel y est rarement couvert d'octobre à juillet. La radiation globale varie en moyenne de 350 à 700 calories par jour et par centimètre carré.
2. L'état hygrométrique : souvent élevé à Dakar, il varie en moyenne de 60 à 90 %. L'humidité de l'air influe sur l'importance de la perte due à la conductibilité apparente "surface chauffée - milieu extérieur".
3. La température extérieure : elle varie de 16 à 30° environ.
4. La vitesse du vent : l'alizé à Dakar durant la saison froide souffle souvent avec violence ; une installation permanente demanderait une protection contre le vent.

Facteur résultant de l'appareil lui-même.

Dans tout le dispositif dont il est question, l'eau circulait horizontalement. Il aurait fallu autrement adopter une inclinaison variable avec l'époque de l'année, ce qui aurait été une source de complication. Les éléments indépendants constitutifs d'un insolateur tel que celui qui vient d'être décrit sont la largeur l, la longueur x, la hauteur de l'eau h, la vitesse v de circulation de cette eau, sa température initiale t_i, enfin le coefficient de perméabilité totale λ déjà défini de l'élément protecteur considéré ; ce dernier, exposé à l'insolation, étant à la température t_m (t est la tempé-

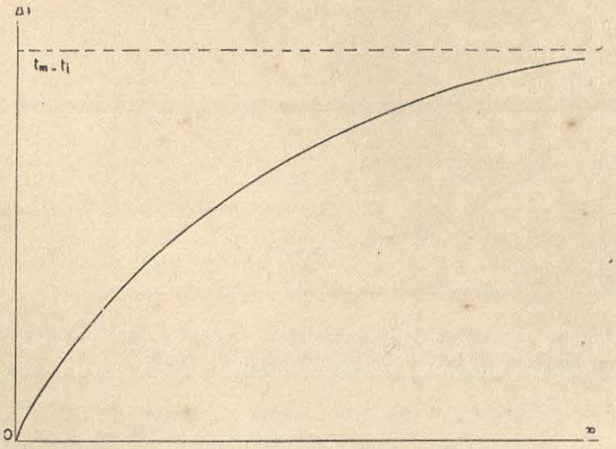


Fig. 5. Variation de l'échauffement de l'eau en fonction de la distance parcourue x.

rature de l'eau qui a parcouru la distance x dans le dispositif). Enfin le débit D est donné par la relation $hlv = D$.

Étudions maintenant l'influence de ces différents facteurs sur la température de l'eau, la quantité de chaleur captée et le rendement de l'installation.

Toutes les données numériques seront exprimées en C.G.S.

a) Température de l'eau.

Nous avons précédemment établi la relation

$$t = (t_i - t_m)e^{-\frac{\lambda x}{hv}} + t_m$$

donnant la température de l'eau à une distance x de l'origine, et la relation donnant l'échauffement Δt de cette eau

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right).$$

La courbe Δt en fonction de x (graphique 5) montre que Δt croît constamment avec la longueur x et tend vers $t_m - t_i$ pour une longueur infinie. L'échauffement décroît au contraire avec la profondeur de l'eau et la vitesse, tandis que sa valeur maximum est $t_m - t_i$ pour h ou $v = 0$. Il tend vers 0 pour h ou $v = \infty$, les autres facteurs étant constants. Une augmentation infinie du débit produit évidemment le même effet qu'une variation correspondante de h ou v.

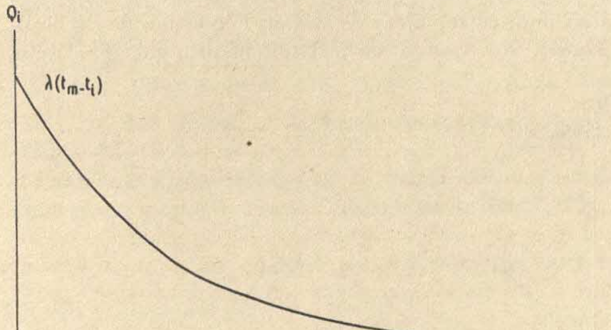


Fig. 6. Variation de la quantité de chaleur captée par seconde par centimètre carré de surface en fonction de la distance x parcourue par l'eau.

On voit que, à partir d'une certaine valeur de x, la température augmente très peu. On n'a donc pas avantage à augmenter la longueur des bassins au-delà d'une certaine limite.

Soit
$$\alpha = \frac{\Delta t}{t_m - t_i} = \frac{t - t_i}{t_m - t_i}$$

le rapport entre l'échauffement cherché et l'échauffement possible. Cherchons la relation entre x et α

$$e^{-\frac{\lambda x}{hv}} = \frac{t - t_m}{t_i - t_m} = \frac{t - t_i}{t_i - t_m} + \frac{t_i - t_m}{t_i - t_m} = 1 - \alpha$$

$$\frac{\lambda x}{hv} = \mathrm{Log}\,\frac{1}{1 - \alpha}$$

$$x = \frac{hv}{\lambda}\,\mathrm{Log}\,\frac{1}{1-\alpha} = \frac{D}{\lambda l}\,\mathrm{Log}\,\frac{1}{1-\alpha}$$

Prenons $\alpha = \frac{9}{10}$, pour $\lambda = \frac{2}{10^4}$, $l = 5$ cm, $D = 1{,}75$ m³/h.

On trouve, en exprimant tout en G.G.S. : $x = 110$ m. Les premiers bassins utilisés avaient une longueur de 30 mètres.

b) Quantité de chaleur recueillie.

Mais l'augmentation de température n'est pas le seul élément à considérer. Il peut être intéressant de connaître la quantité de chaleur reçue par l'eau, et différentes expressions sont possibles. On peut considérer la quantité de chaleur reçue par seconde sur une surface de 1 cm² dont la température est t. La définition de λ nous donne :

$$Q_i = \lambda(t_m - t)$$

et en remplaçant t par sa valeur :

$$Q_i = \lambda(t_m - t_i)\,e^{-\frac{\lambda x}{hv}}$$

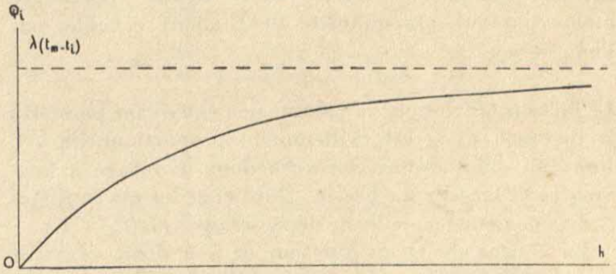


Fig. 7. Variation de la quantité de chaleur captée par seconde par centimètre carré de surface en fonction de la profondeur de l'eau h.

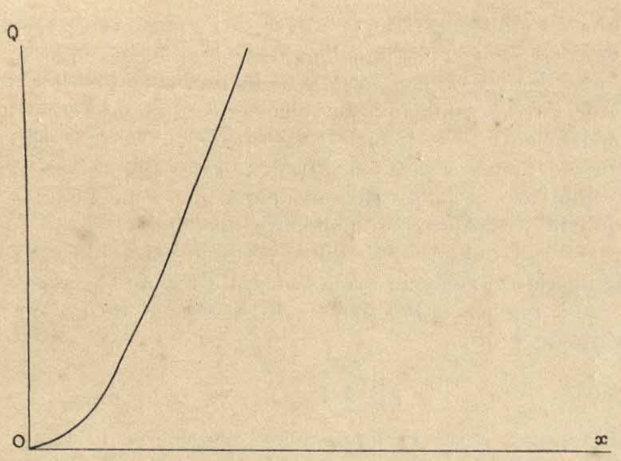


Fig. 8. Variation de la quantité de chaleur captée par l'eau en fonction de la distance *x* parcourue par l'eau.

La courbe a l'allure indiquée sur le graphique 6 : Q_i prend sa valeur maximum $\lambda(t_m - t_i)$ au début du parcours et tend vers 0, tandis que pour une longueur infinie, les températures de la couche chauffante et de l'eau s'étant égalisées, il n'y a plus de transmission de chaleur.

Les résultats seraient inversés si l'on faisait croître *h* ou *v* (graphique 7). Pour une hauteur d'eau très petite l'équilibre s'établit instantanément et il n'y a plus de transmission de chaleur.

Il est beaucoup plus intéressant de connaître la quantité de chaleur reçue par l'eau sur une surface de 1 cm² durant le temps nécessaire pour un certain parcours. Pendant ce temps $d\theta$ très court, l'eau a parcouru la distance $dx = vd\theta$.

Donc la quantité de chaleur reçue est :

$$dQ = \lambda(t_m - t)\frac{dx}{V} = \lambda(t_m - t_i)e^{-\frac{\lambda x}{hv}}\frac{dx}{V}$$

d'où

$$Q = \int_0^x \lambda(t_m - t_i)e^{-\frac{\lambda x}{hv}}\frac{dx}{V} = h(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)$$

Ceci pour une surface de 1 cm². Et pour toute la surface, chaque centimètre carré ayant effectué le même parcours, la quantité de chaleur recueillie par l'eau sera :

$$Q = hlx(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right).$$

Le facteur *hlx* désigne le volume de l'eau ayant parcouru la distance *x*; Q est évidemment proportionnelle à *l*. Pour un débit donné, on aura donc avantage à augmenter la largeur du bassin. Dans tous les cas la quantité de chaleur recueillie ne dépassera pas $hlx(t_m - t_i)$.

La courbe de Q en fonction de *x* à débit constant (graphique 8) montre que Q croît avec la longueur du bassin. La courbe devient une droite d'autant plus rapidement que *h* et *v* sont plus petits, donc que le débit est plus petit.

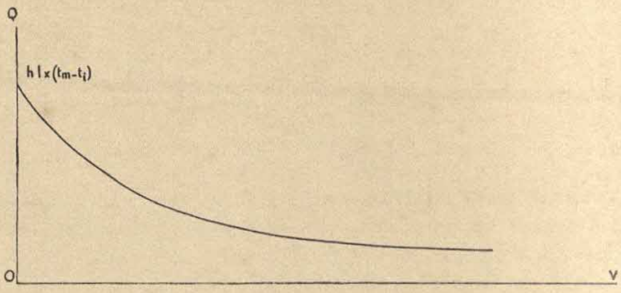


Fig. 9. Variation de la quantité de chaleur captée par l'eau en fonction de la vitesse *v* de passage de l'eau.

Par contre Q varie en sens inverse de la vitesse de passage de l'eau (graphique 9). Pour une vitesse nulle, la quantité de chaleur atteint la valeur limite (cas de l'eau stagnante).

La variation de Q avec la profondeur de l'eau est moins évidente. Pour une vitesse donnée la quantité de chaleur augmente avec la profondeur de l'eau, c'est-à-dire avec le débit (graphique 10). La limite de Q est : $\lambda(t_m - t_i)lx\frac{x}{V}$ qui représente la quantité de chaleur maximum susceptible d'être donnée à l'eau pendant le temps $\frac{x}{V}$. Mais l'échauffement diminue quand *h* augmente ; on n'a donc pas intérêt à augmenter *h* quand la limite de Q est susceptible d'être atteinte.

Cherchons pour quelle valeur de *h* la quantité de chaleur atteint les neuf dixièmes de la quantité de chaleur limite, dans le cas où l'eau met dix heures pour parcourir toute la longueur du bassin :

$$\frac{9}{10}\frac{\lambda x^2(t_m - t_i)}{V} = hlx(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)$$

En prenant $\frac{x}{V} = \theta = 36.000$ secondes, on trouve $h = 30$ cm, hauteur qui avait effectivement été employée. Mais pour cette valeur de *h*, dans l'équation de l'échauffement, on trouve un échauffement égal aux deux

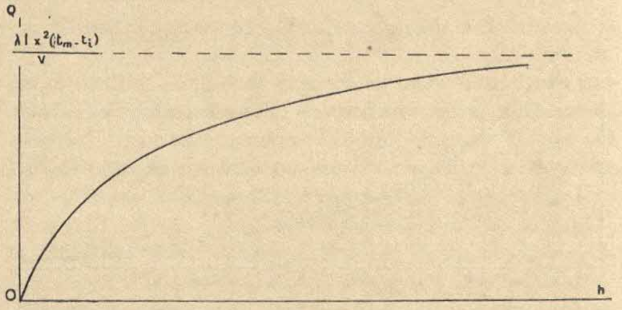


Fig. 10. Variation de la quantité de chaleur captée par l'eau en fonction de la profondeur de l'eau *h*.

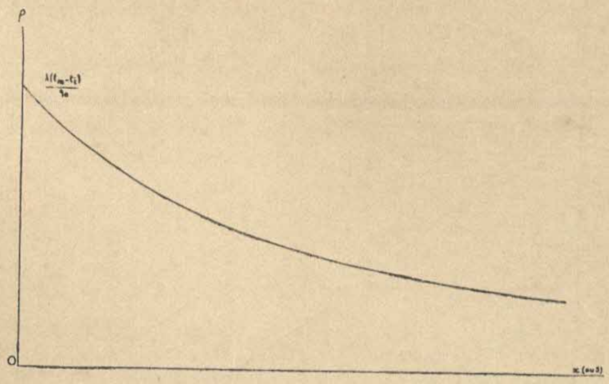


Fig. 11. Variation du rendement ρ en fonction de la distance x parcourue par l'eau.

dixièmes de l'échauffement limite, bien différent par conséquent de l'échauffement limite.

LE RENDEMENT

Il nous reste à définir le rendement ρ de l'installation : c'est le rapport entre l'énergie calorifique Q absorbée par l'eau et l'énergie calorifique incidente Q_0 pendant le même temps et pour une même surface.

On aura donc pour une surface S de 1 cm² et le temps $\frac{x}{V}$, q_o étant la quantité de chaleur incidente par centimètre carré et par seconde :

$$\rho = \frac{Vh\,(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)}{q_0\,\frac{x}{V}} = \frac{Vh\,(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)}{q_0\,x}$$

qui peut encore s'écrire :

$$\rho = \frac{D(t_m - t_i)\left(1 - e^{-\frac{\lambda xl}{D}}\right)}{q_0 xl} = \frac{D(t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)}{q_0 S}$$

La courbe de ρ en fonction de V, h, ou D a la même forme que la courbe de Q en fonction de h. Elle croît constamment et sa limite est $\frac{\lambda\,(t_m - t_i)}{q_0}$; au contraire elle décroît si on fait croître x ou S. Sa valeur est $\frac{\lambda\,(t_m - t_i)}{q_0}$ pour x ou $S = 0$, et vaut zéro pour x ou $S = \infty$. La courbe a la forme indiquée sur le graphique 11.

Calculons à titre d'exemple la valeur limite du rendement en prenant comme échauffement limite 10° :

$\lambda = \frac{2}{10^4}$ et $q_0 = \frac{1}{60}$ calorie par seconde (600 calories en dix heures). On trouve $\rho = 0{,}12$.

CONSIDÉRATIONS PRATIQUES

Si l'on se propose de réaliser un dispositif destiné à obtenir la valeur la plus importante d'une des variables, le problème est résolu ; il suffit de se reporter à l'une des courbes ci-dessus. Mais, dans la grande majorité des cas, l'utilisateur recherche la meilleure utilisation d'un procédé : obtenir un échauffement sans pour cela avoir de valeurs trop basses pour Q et ρ. Le problème ainsi présenté apparaît complexe puisqu'un accroissement d'un des facteurs h, v ou x pris isolément ne produit pas un accroissement simultané de trois fonctions Δt, Q, ρ comme le montre le tableau suivant :

Variable si

$h \nearrow$	$t \searrow$	$Q \nearrow$	$\rho \nearrow$
$v \nearrow$	$t \searrow$	$Q \searrow$	$\rho \nearrow$
$x \nearrow$	$t \nearrow$	$Q \nearrow$	$\rho \searrow$

Proposons-nous de rechercher la meilleure solution, étant donné qu'au voisinage de la limite une variation considérable de la variable produit une faible variation de la fonction.

Les accroissements relatifs par rapport aux limites d'échauffement et de quantité de chaleur ont pour expression :

$$\frac{\Delta t}{(t_m - t_i)} = 1 - e^{-\frac{\lambda x}{hv}} \qquad \frac{Q}{Q_l} = \frac{Vh}{\lambda x}\left(1 - e^{-\frac{\lambda x}{hv}}\right)$$

en prenant $Q_l = \frac{\lambda l x^2}{V}\ (t_m - t_i)$ valeur limite de la quantité de chaleur susceptible d'être captée.

Les courbes $\frac{\Delta t}{(t_m - t_i)}$ et $\frac{Q}{Q_l}$ en fonction de $\frac{\lambda x}{hv}$ sont représentées sur le même graphique (12) ; leur point d'intersection a pour abscisse $\frac{\lambda x}{hv} = 1$.

L'ordonnée commune a alors pour valeur 0,63, ce qui revient à dire que pour $\frac{\lambda x}{hv} = 1$ l'élévation de température et la chaleur captée atteignent les soixante-trois

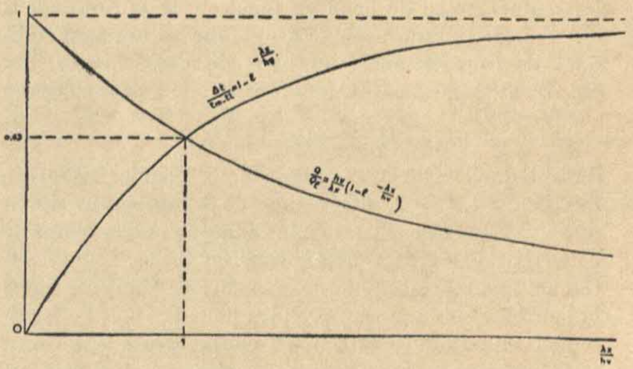


Fig. 12. Variation du rapport de l'échauffement vrai à l'échauffement limite. Variation du rapport de la quantité de chaleur captée à la quantité de chaleur susceptible d'être captée en fonction de $\frac{\lambda v}{hv}$.

centièmes de leur limite. Enfin le calcul montre qu'il en est de même pour ρ. Pour des valeurs de $\frac{\lambda x}{hv}$ inférieures à 1, on augmente la chaleur captée, mais on diminue l'élévation de température et réciproquement.

La condition $\frac{\lambda x}{hv} = 1$ peut s'écrire $\frac{\lambda S}{D} = 1$.

D'où $D = \lambda S$. Si l'on prend $\lambda = \frac{2}{10^4}$, on trouve pour les bassins de 30 m × 5 m, D = 1,08 m³/h et pour ceux de 1 m de large D = 0,2 m³/h. Les débits employés (1,75 m³/h et 1 m³/h) favorisaient donc la quantité de chaleur captée, au détriment de la température.

On voit qu'on a ainsi une relation entre D, S et λ. D'où l'utilité de connaître λ.

DÉTERMINATION EXPÉRIMENTALE DE λ

Dans ce qui précède, nous avons pris $\lambda = \frac{2}{10^4}$. Comment le connaît-on? λ a été mesuré. D'après la définition même de λ, il fallait chercher la quantité de chaleur qui traversait, par seconde, une surface de 1 cm² de mazout dont l'épaisseur est de 1 mm, quand on maintient une différence de température de 1° entre les deux surfaces de film.

Un vase de Dewar destiné à éliminer la perte de chaleur par la paroi est rempli d'eau jusqu'au bord ; la partie supérieure de cette eau est recouverte d'un film de mazout de 1 mm d'épaisseur. La source de chaleur est une lampe à incandescence de 300 watts et les distances sont telles que le solarimètre Gorczinski placé à la même distance de la lampe que le mazout indique une radiation de 1,4 cal/cm²/minute.

La surface du vase est de 176 cm², sa profondeur est 28 cm. Les températures sont évaluées grâce à des couples thermo-électriques, précis au dixième de degré et placés respectivement à la surface (donc dans le mazout) à 8 cm et à 18 cm de profondeur. Les courbes donnant les températures de l'eau en fonction de la profondeur ont l'allure indiquée par le graphique 13, où sont indiqués les échauffements au bout de deux heures, dix heures, et trente heures. L'expression de λ peut s'écrire :

$$Q = \lambda(t_m - t_i)\, S\theta$$

dans laquelle Q est la quantité de chaleur absorbée par l'eau, $t_m - t_i$ l'élévation de température maximum, S la surface exposée à la radiation et θ le temps de cette exposition, le tout exprimé en C.G.S. Q aux différents instants est donnée par la surface comprise entre la courbe et les axes, on prendra pour $t_m - t_i$ l'échauffement maximum de l'eau en contact avec le mazout.

L'expérience montre que λ décroît au début de l'irradiation. C'est durant la deuxième heure d'expérience que sa valeur devient constante. Le calcul donne pour le mazout 5×10^{-4} C.G.S. au bout de la première heure, tandis que la valeur adoptée pour une durée normale d'irradiation de dix heures est $2{,}1 \times 10^{4}$ (on a pris 2 pour les calculs approchés).

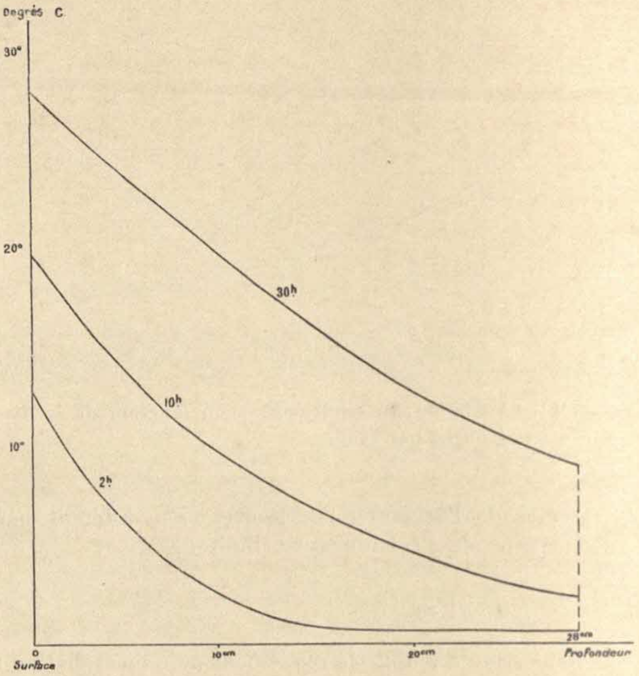


Fig. 13. Détermination de γ. Variation de l'échauffement de l'eau en fonction de la profondeur après différentes durées d'exposition dans un vase de Dewar.

ACCROISSEMENT DE $t_m - t_i$

On a vu que pour un dispositif expérimental donné les valeurs de Δt, Q et ρ sont fonctions linéaires de $t_m - t_i$. On aura donc avantage à augmenter t_m.

Un moyen simple est évidemment d'utiliser l'effet de serre, c'est-à-dire de recouvrir d'un ou de plusieurs verres l'élément protecteur de l'eau.

Soit q l'intensité de la radiation globale par centimètre carré et par seconde, égale à celle qui arrivait dans le cas précédent sur la surface du mazout ; si μ est le coefficient de transmission du verre et n le nombre de verres, il n'arrivera sur le film protecteur de mazout que $q_v = q\mu^n$. En même temps il y aura rayonnement de la chaleur de l'air emprisonné vers le milieu extérieur. Si λ est le coefficient de conductibilité apparente air-verre-air, la quantité de chaleur qui sera emprisonnée par les verres sera :

$$q_v = q\mu^n - \frac{\lambda\,(t_m - t_a)}{n}$$

$t_m - t_a$ étant la différence de température mazout-air.

La courbe $q = f(n)$ (graphique 14) montre que q passe par un maximum pour $n = 2$. En pratique l'addition d'un seul verre au-dessus du mazout a approximativement multiplié les limites par 1,5.

CONCLUSION

Ce qui précède n'est qu'un aperçu sommaire des conditions théoriques de fonctionnement d'un insolateur. Il faudrait dans la réalisation tenir compte de facteurs qui ont été nécessairement négligés ici. Ainsi on pourrait expliquer certaines discordances particulières entre la pratique et la théorie. Dans le cas par exemple où on superpose plusieurs verres, les valeurs limites de l'échauffement et du rendement ne semblent pas à première vue suivre exactement la loi théorique ; on sera sans doute amené à tenir compte de la convection, étroitement liée à l'écartement des vitres. Mais dans la grande majorité des cas les valeurs fournies par les calculs qui viennent d'être développés correspondent aux résultats pratiques quand on prend soin de travailler avec des appareils se rapprochant de conditions idéales, ainsi que le montrent des expériences qui ont lieu actuellement à Dakar, avec de l'eau protégée par une tôle et du verre.

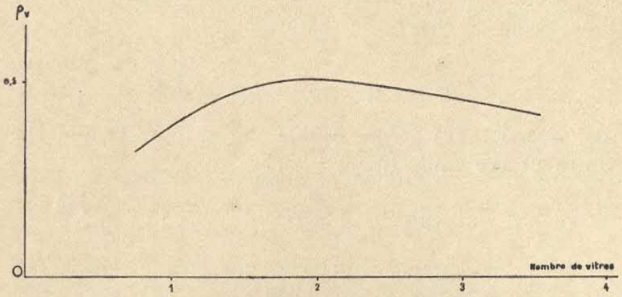


Fig. 14. Variation du rapport ρ_v de l'énergie totale transmise à l'énergie incidente reçue en fonction du nombre de verres interposés.

Les résultats théoriques et pratiques sont extrêmement encourageants. La question la plus délicate qui reste à examiner actuellement est celle du prix de revient par calorie : il faut évidemment que l'appareil soit rentable. L'ensemble fera l'objet d'une prochaine publication.

METHODS OF CAPTURING SOLAR HEAT

by

H. Masson

SUMMARY

The laboratory for research on the utilization of solar energy at Dakar is of recent date. It has only existed officially for eight months, although in fact the experiments conducted there were started two years ago by the late Mr. Nizery. They have been extended with the support of the semi-public company Energie des Mers and the General Government of French West Africa. The aim of these experiments, which have been greatly encouraged by Unesco, is to find a way of heating water by utilizing the effects of solar radiation.

The preliminary experiments were carried out with stagnant water. Concrete tanks, with a surface of about 1 m^2. and a depth of 30 cm., were filled with water and exposed to the sun's rays. The water grew warm, but evaporated at the same time. To prevent evaporation, the surface of the water was covered with a substance which allowed the sun's rays to penetrate, but kept the water from contact with the outside air. Thus as the water heated, there was less evaporation and, in some cases, none at all. Such thin protecting surfaces (about 1 mm. thick) can be either liquid (vaseline or diesel oil) or solid (a glass framework or blackened sheet-iron). In certain cases, they can be combined, e.g. a glass framework and diesel oil, a glass framework and blackened sheet-iron, or several layers of glass and sheet-iron. In one control tank the surface of the water was left in contact with the air.

It was thus possible to establish a coefficient $K = \frac{\Delta t \times 100}{Q_0}$ for each apparatus, equal to the relationship between the heated surface of the water and the quantity of incident heat per area of surface for a duration equal to that of insolation. The total radia-

tion, measured with a Gorczinski solarimeter, is taken to equal the quantity of incident calorific energy. Temperatures during the experiment were measured with a mercury thermometer graduated in fifths of a degree. The values found for K vary between 1.07 for pure water and 1.70 for diesel oil covered with glass.

The heating of stagnant water, however, is of little interest. What is wanted is running water which, when heated by solar radiation, supplies calories capable of utilization.

That is why we undertook a second series of experiments with water flowing through tanks 30 m. long, 5 m. wide and 30 cm. deep. One of the tanks served as a control. The other was covered with a film of vaseline or diesel oil 1 mm. thick. Inflow and outflow temperatures were measured with thermo-electric cells. The curves indicating the rise in temperature of the water over 24 hours were of the same form for the protected tank as for the tank exposed to the air, the degree of heating of course being greater in the former. The flow was 1.75 m.^{3} per hour. When the width of the tanks was reduced to 1 m., the flow was fixed at 0.9 m.^{3} per hour. On the basis of the flow and rise in average temperature during the period of insolation, or over 24 hours, it is possible to calculate the efficiency of the process, that is, the number of calories gained in a given time. The output can thus be calculated, since the total radiation is also measured.

In practice, this apparatus is not perfect. In the first place, liquid films do not last indefinitely because dust makes them less permeable to solar radiation. Moreover, diesel oil has the disadvantage of evaporating and consequently of having to be changed more often. Further, the trade wind often blows violently in our regions and causes the protective liquid to accumulate against one wall of the tank, thus uncovering a large part of the surface of the water. This difficulty had to be overcome by a wooden grille system, cutting up the surface of the water into areas of 1 m.^{2}. Although this grille prevented the film from moving, it threw shadow on the water. The final results showed that calories were gained mainly after insolation, since the film prevented nocturnal cooling; but that was not exactly the aim which we had in mind, so another apparatus had to be devised.

One of the advantages of these experiments, however, was to supply certain data on which we were able to base a theoretical study which led to far more satisfactory results.

In this preliminary study, we will suppose that the walls of the apparatus are perfectly heat proof. If it be assumed that, under the influence of solar radiation, the temperature of the protective film is t_m, higher than the initial temperature t_i of the water, then it can be said that, at the beginning of its course, the water receives $\lambda\,(t_m - t_i)$ calories per cm.^{2} per second; λ is the coefficient of apparent conductivity of the protective layer.

At a distance x from the point of departure, taking v as the velocity of the water, h as its depth and t as temperature, the subsequent heating of the water can be expressed as:

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)$$

which can also be written with the insertion of θ, the time taken to cover the distance:

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda\theta}{h}}\right)$$

and if one takes as a variable the outflow D and the width of the tank l:

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda xl}{D}}\right) = (t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)$$

S being the surface subject to insolation. Thus the influence of one factor or another can be ascertained, provided that the others are constant. In particular, these expressions show that the temperature increases and tends towards a limit when depth or velocity diminish.

Similarly, the quantity of heat absorbed by the water during its course can be expressed alternatively as:

$$Q = hlx\Delta t = D\theta \times \Delta t = hlx(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)$$
$$= hlx(t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)$$

If the different factors are varied, Q increases or decreases, but remains between 0 and a limiting value $\lambda S\theta(t_m - t_i)$, which can be expressed as

$$\frac{\lambda l x^2}{v}\left(t_m - t_i\right)$$

Finally, the output of the whole apparatus may be defined as the ratio between the calorific energy Q absorbed by the water during its course and the incident calorific energy q, which it has received during the same time. If all this is expressed in terms of a surface area, the result is:

$$\rho = \frac{Vh(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right)}{q_0 x} = \frac{D(t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)}{q_0 S}$$

the limiting value of this output is:

$$\frac{\lambda(t_m - t_i)}{q_0}$$

A study of the whole of the preceding expression shows that an increase in one of the variables h, v or x, taken separately, does not produce a simultaneous increase of the three functions Δt, Q and ρ. For the problem with which we are dealing, however, it is interesting to obtain simultaneously the highest possible values for Δt, Q and ρ.

Calculation shows that if one takes

$$\frac{\lambda x}{hV} = \frac{\lambda xl}{D} = \frac{\lambda S}{D} = 1,$$

values equal to $\frac{63}{100}$ of their limit are obtained simultaneously for Δt, Q and ρ. This provides a basis for obtaining an increase or decrease in relation to the limit by means of appropriate changes of the variables.

The expression $\frac{\lambda S}{D} = 1$ gives an interesting relationship between D and S if the value of λ is known. We therefore endeavoured to measure λ by experiment, keeping as close as possible to theoretical conditions. A certain volume of water in a Dewar flask was exposed to calorific radiation of known intensity. The surface of the water was covered with a liquid film or a solid protective layer. The degree of warming of the water was calculated by means of thermo-electric cells placed at different depths. The measurements then showed that the value of λ for one and the same substance varies according to the irradiation period and tends towards a limit which, if the irradiation period is sufficiently long, is the same for different substances.

There seems little hope, therefore, of increasing the output considerably by selecting a protective substance of high λ. As the factor $(t_m - t_i)$ is included in the expression of the limiting value of ΔT, Q and ρ, a better method is to try to find a means of increasing t_m. The simplest solution is of course to produce a greenhouse effect by covering the protective element with one or more layers of glass. A loss of calories naturally results, on account of the absorption and radiation of the glass. Calculation shows that this loss is smallest when two layers of glass are placed one on top of the other. Experiments undertaken with one layer of glass placed on the sheet-iron protecting the water proved that the sheet-iron reached maximum temperatures of 90° C. or even 100° C. This improved the output considerably. Systematic experiments are being conducted and will be described in a forthcoming publication. Results already appear to be encouraging, despite technical difficulties and the fact that the cost per calorie is still too high.

SOBRE EL PROCEDIMIENTO DE CAPTURA DEL CALOR SOLAR

por

H. Masson

RESUMEN

El laboratorio de investigaciones sobre la energía solar establecido en Dakar es de reciente creación. Aunque fué inaugurado oficialmente hace ocho meses, en realidad, las experiencias que en él se llevan a cabo comenzaron hace ya dos años por iniciativa del difunto Sr. Nizery. Dichas experiencias se han desarrollado con el apoyo de la Sociedad de Economía Mixta "Energie des Mers" y del gobierno general del África Occidental francesa, y han recibido asimismo considerable estímulo por parte de la Unesco. El fin de tales investigaciones es determinar los métodos más eficaces para el calentamiento del agua haciendo uso de la energía solar.

Los primeros experimentos se realizaron con agua estancada en depósitos de cemento de un m² de superficie y 30 cm de profundidad aproximadamente, en los que el agua quedaba expuesta a los rayos del sol. Sin embargo, como el agua al calentarse también se evaporaba, fué necesario, para evitar la evaporación, cubrir la superficie líquida con una substancia que dejara pasar las radiaciones solares e impidiera al mismo tiempo el contacto del agua con la atmósfera, consiguiéndose así el calentamiento del agua con una evaporación mínima o, en algunos casos, enteramente nula. Esas substancias protectoras, de reducido espesor (1 mm aproximadamente), podían ser líquidas (aceite de vaselina o masut), sólidas (vidrio o chapa fina pintada de negro) o mixtas (vidrio y masut, vidrio y chapa o varias láminas de vidrio y chapa). En un estanque de control, el agua se deja sin protección alguna.

De este modo se ha podido establecer para cada dispositivo un coeficiente K $\frac{\Delta t \times 100}{Q_0}$, igual a la relación entre el calentamiento de la superficie del agua y el calor incidente por unidad de superficie durante el tiempo de insolación. Por valor de la cantidad de calor incidente se toma la radiación global medida con el solarímetro de Gorczinski. Las temperaturas alcanzadas durante el experimento se midieron con un termómetro de mercurio graduado en quintos de grado. Los valores observados de K variaban entre 1,07 en el caso del agua pura y 1,70 en el del masut recubierto de cristal.

Sin embargo, el calentamiento del agua estancada no presenta gran interés. En la práctica es preciso emplear agua corriente cuyo calentamiento por insolación producirá las calorías utilizables.

Para ello, se llevó a cabo una segunda serie de experiencias en las cuales se hacía correr el agua por dos canales de 30 metros de largo, 5 de ancho y 30 centímetros de profundidad. Uno de ellos servía de control; en el segundo, el agua se hallaba cubierta de una película de aceite de vaselina o de masut de 1 mm de espesor. Unos termómetros de resistencia colocados a la entrada y a la salida de los canales servían para determinar la temperatura del agua en esos puntos. Las curvas que indican la elevación de la temperatura durante veinticuatro horas presentan la misma forma para ambos canales, pero, como es natural, el calentamiento es más importante en el caso del canal recubierto que en el del canal de control. El flujo del agua era de 1,75 m^3 por hora. Más tarde se redujo la anchura de los canales a 1 metro y el flujo a 0,9 m^3 por hora. El conocimiento del flujo y de la elevación de la temperatura media durante la insolación o durante veinticuatro horas permite calcular la eficacia del procedimiento: es decir, el número de calorías economizadas en un tiempo dado. Se puede así determinar el rendimiento, dado que por otra parte se mide la radiación global.

En realidad este dispositivo dejaba bastante que desear. En primer lugar, las películas líquidas tienen una duración limitada debido al polvo que sobre ellas se deposita y hace que gradualmente pierdan su transparencia. Además, el masut se evapora y es preciso, por tanto, renovarlo frecuentemente. Por otra parte, los vientos que soplan en esas regiones son a menudo violentos y acumulan la capa protectora de líquido contra un muro del canal, dejando desprovista una gran superficie de agua. Se procuró remediar este inconveniente construyendo unos encuadres de madera que dividen la superficie del agua en secciones de 1 m^2 cada una ; pero, si bien este encuadre impedía el desplazamiento de la película superficial, proyectaba, por otra parte, una sombra sobre el agua. Además, los resultados han probado que la ganancia de calorías se producía después de la insolación, como consecuencia de la protección que la película significaba contra el enfriamiento nocturno, lo cual no era precisamente el fin buscado. Se hizo pues evidente la necesidad de modificar la instalación.

Sin embargo, una de las ventajas de los experimentos descritos ha sido suministrar una serie de datos que pueden servir de base a un estudio teórico que facilite la mejora considerable de los resultados.

En este primer estudio suponemos que las paredes del canal son perfectamente calorífugas. Si admitimos que bajo la influencia de las radiaciones solares la temperatura de la película es t_m, más elevada que la temperatura inicial del agua (t_i), podemos decir que el agua recibe desde el principio de su recorrido, por cm^2 y por segundo $\lambda(t_m - t_i)$ calorías; λ es el coeficiente de conductibilidad aparente del elemento protector.

A una distancia x del punto de partida, el agua, que corre con una velocidad v y una profundidad h, adquiere la temperatura t y sufre un calentamiento:

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda}{hv}}\right),$$

que también podemos escribir haciendo intervenir θ, el tiempo de recorrido:

$$\Delta t = (t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)$$

y si queremos utilizar como variable el flujo D y la longitud 1 del canal:

$$\Delta t = (t_m - t_i)\,(1 - e^{-\frac{\lambda x 1}{D}}\Big) = (t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right)$$

donde S es la superficie sometida a insolación. De este modo, podemos hacer resaltar la influencia de uno u otro de esos factores, ya que los demás son constantes. Estas expresiones demuestran en particular que la temperatura crece y tiende hacia un valor límite cuando disminuyen la profundidad o la velocidad.

Del mismo modo podemos buscar la expresión que nos dé la cantidad de calor capturada por el agua durante su recorrido. Según el caso escribiremos:

$$Q = hlx \times \Delta t = D\theta \times \Delta t = hlx(t_m - t_i)\left(1 - e^{-\frac{\gamma x}{hv}}\right)$$

$$= hlx(t_m - t_i)\left(1 - e^{-\frac{\lambda S}{D}}\right).$$

Si hacemos variar los diferentes factores, Q crecerá o disminuirá pero continuará comprendido entre 0 y un límite superior $\lambda S\theta(t_m - t_i)$, que podemos expresar así : $\frac{\lambda\, lx^2}{v}(t_m - t_i)$.

En fin, podemos definir el rendimiento del proceso por medio de la relación entre la energía calórica Q absorbida por el agua durante su recorrido y la energía calorífica recibida por ella durante el mismo tiempo. Si reducimos todo a la unidad de superficie tendremos:

$$\rho = Vh(t_m - t_i)\left(1 - e^{-\frac{\lambda x}{hv}}\right) = \frac{D-(t_m t_i)\left(1 - e^{\frac{\lambda S}{D}}\right)}{q_0 S}$$

cuyo límite superior de rendimiento será:

$$\frac{\lambda(t_m - t_i)}{q_0}$$

El estudio del conjunto de la expresión precedente muestra que el aumento de una de las variables h, v o x, tomada aisladamente, no produce un aumento simultáneo de las tres funciones Δt, Q y p. En el problema que nos ocupa, nos interesa obtener simultáneamente valores de Δt, Q y p lo más elevados posibles. El cálculo muestra que si tomamos

$$\frac{\lambda x}{hV} = \frac{\lambda x l}{D} = \frac{\lambda S}{D} = 1,$$

se obtiene simultáneamente para Δt, Q y ρ valores iguales a $\frac{63\ i}{100}$ de su límite. Poseemos ahí un punto de referencia que puede servirnos de base si queremos aproximarnos o alejarnos del valor límite mediante una variación conveniente de las variables.

La expresión $\frac{\lambda S}{D} = 1$ produce una relación interesante entre D y S si se conoce λ. Eso explica nuestros esfuerzos por determinar experimentalmente λ aproximándonos a las condiciones teóricas. Una masa de agua contenida en un vaso de Dewar se expone a una radiación calorífica de valor conocido. La superficie del agua ha sido recubierta de una película líquida o una substancia protectora sólida. El calentamiento de la masa de agua se conoce gracias a pares termoeléctricos dispuestos a diferentes profundidades. Las temperaturas muestran que el valor de λ en una misma substancia varía según el tiempo de irradiación y tiende hacia un valor límite común a las diferentes substancias para un tiempo de irradiación suficientemente largo.

Parecía por lo tanto difícil mejorar considerablemente el rendimiento del canal seleccionando una substancia protectora de un valor λ elevado. Como el factor $(t_m - t_i)$ entra en la expresion del valor límite de Δt, de Q y de ρ, parecía más interesante buscar un procedimiento de elevar t_m. Para ello, el dispositivo más simple es evidentemente utilizar el efecto de retención calórica cubriendo el elemento protector con uno o varios vidrios, aunque, por otra parte, se produce una evidente pérdida de calor debida a la absorción e irradiación del vidrio. Sin embargo el cálculo muestra que esta pérdida es mínima en el caso de dos vidrios superpuestos. Las experiencias realizadas con una lámina de vidrio colocada sobre una chapa que actúa como cubierta del agua han dado para la chapa temperaturas máximas que llegaban hasta 90° C y, en ciertos casos, hasta 100° C. Vemos pues que el rendimiento ha mejorado considerablemente. En la actualidad se están llevando a cabo mediciones sistemáticas que aparecerán en una próxima publicación. Los resultados de estos experimentos parecen ser ya alentadores, a pesar de las dificultades técnicas de realización y de que el costo de producción por caloría es aún demasiado elevado.

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SOLAR ENERGY IN INDIA

by

L.A. Ramdas and S. Yegnanarayanan

INTRODUCTION

The sun sustains life both directly and indirectly and is the ultimate source of all energy on the earth. Photosynthesis is the primary process by which plants live and grow. Energy resources such as coal and oil represent the products of photosynthesis in ages long past, which are preserved for us. The amount of solar energy used in photosynthesis is but a very small percentage of the available solar energy, and attempts to utilize more and more of it by increasing the plant cover on the earth on a well-planned basis deserve active encouragement. Besides providing food for herbivorous animals and human population, the sun is the chief influence on the climate of the earth and provides energy for the motion of the winds and of the waves. Only when we work out a complete energy balance sheet do we begin to realize how vital is the role played by the sun.

The history of man's quest for power and energy resources is practically that of human progress and civilization. We are now beginning to realize how rapidly the world assets of coal and oil are dwindling. The atomic age has begun, but it is still a long way to the harnessing of atomic energy for industrial and other peaceful purposes, and even this can be pursued only by the scientifically advanced nations. Our thoughts, therefore, naturally turn to other more readily available sources such as the greater utilization of direct solar radiation and the energy of the winds and, in favourably situated places, even the energy of sea waves for industrial, domestic and agricultural purposes. In the present report we shall make a brief survey of the solar energy that may be available for use in India.

SOLAR ENERGY

It is estimated that every year the sun sends out radiation the heat equivalent of which is 400 billions of trillions (4×10^{23}) of tons of anthracite coal! The earth, which is at a mean distance of 93,000,000 miles from the sun, intercepts less than $\frac{1}{2,000,000,000}$ part of the solar output. The intensity of solar radiation outside the limit of the earth's atmosphere is estimated to be 1.94 gramme calories per cm.^{2} per minute for normal incidence of the incoming rays. When this radiation is spread out into a spectrum, the maximum energy occurs at about 0.5 λ (5,000 A.u.).

When solar radiation passes through the atmosphere, it is depleted by the process of (a) absorption by certain components of the atmosphere; (b) molecular scattering by the gases in the atmosphere; and (c) scattering by dust and other impurities.

The constituents of dry air expressed as percentages by volume are nitrogen 78.03 per cent, oxygen 20.99 per cent, argon 0.94 per cent, carbon dioxide 0.03 per cent, neon 0.0012 per cent, helium 0.0004 per cent, krypton 5×10^{-6} per cent, and xenon 5×10^{-7} per cent. The composition of the atmosphere is uniform up to the heights for which data are available. In addition to the above, there are of course (a) water vapour, which decreases rapidly with height, becoming almost negligible above the tropopause and (b) the small percentage of ozone in the upper atmosphere (10-50 km.) with maximum concentration at 25 km. (the total ozone content is of the order of 1.5 to 4.5 mm. at N.T.P.). Ozone is produced under the action of the ultra-violet radiation from the sun, the extreme ultra-violet being responsible also for converting some of the molecules of oxygen into atomic oxygen.

The constituents of the atmosphere which take a significant part in the absorption of solar radiation are: (a) oxygen atoms in the uppermost regions, absorbing the extreme ultra-violet (0.12-0.18 μ); (b) ozone, absorbing mainly in the ultra-violet region, the Hartley Band, 0.20-0.33 μ and to a much smaller extent in the visible (Chappuis) band, 0.44-0.76 μ; (c) water vapour absorbing in the near infra-red bands centred at 0.93,

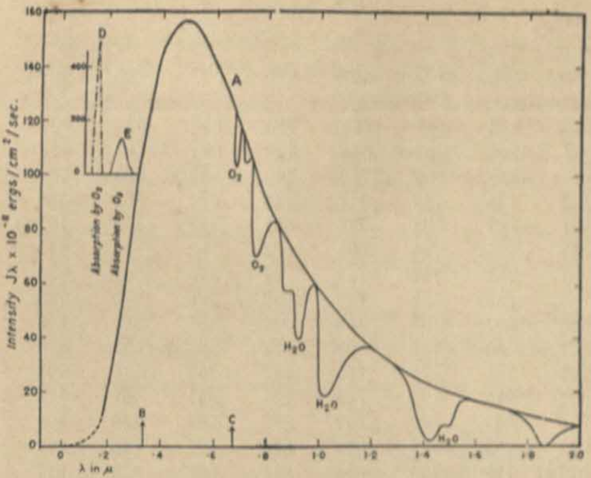

Fig. 1. Distribution of energy in solar radiation.

1.13, 1.42 and 1.47 μ, and (d) carbon dioxide in the near infra-red at 2.7.

Practically all the radiation in the ultra-violet region at wavelengths smaller than 0.33 is cut off by the oxygen atoms and ozone in the upper atmosphere. On the long wavelength side beyond 0.68, the solar spectrum shows a number of absorption bands due to oxygen molecules and water vapour. Those due to water vapour at 0.93 μ, 1.13 μ, 1.42 μ and 1.47 μ are important, and cut off a significant percentage of the solar radiation in the near infra-red region. The CO_2 band at 2.7 μ will not affect the total radiation reaching the earth's surface materially. The cutting off of the extreme ultra-violet by oxygen and ozone is of immense significance to life on our planet as we can tolerate these radiations only in minute doses, any excess being fatal.

The blue colour of the sky is due to the solar radiation diffused by the molecules in the air, which scatter the shorter wavelengths preferentially according to the inverse fourth power law of Rayleigh.

The transmission factor associated with atmospheric scattering is given by:

$$T_{a\lambda} = 10^{-0.00380/\lambda^4}$$

where λ is in μ; the pressure is 760 mm. of Hg and the sun is at the zenith. The transmission through water vapour is given by:

$$T_{w\lambda} = 10^{-0.0075/\lambda}$$

when the sun's rays are vertical and the amount of precipitable water is 20 mm. Similarly, when the dust content is of the order 800 per cm.³:

$$T_{d\lambda} = 10^{-0.0353}.$$

The combined transmission T (at the wavelength), when the barometric pressure is *p*, precipitable water *w*, dust content *d* and when the sun's rays are incident at an angle to the vertical, is given by Bouger's equation [7][1]:

$$T\lambda = [(T_{a\lambda})^{p/760} \times (T_{w\lambda})^{w/20} \times T_{d\lambda})^{d/800}]m$$

where the air mass m = sec. θ is equal to 1 when $\theta = 0$.

The foregoing values of Tλ, when corrected for absorption due to ozone, provide a basis for the computation of solar radiation which reaches the earth's surface in clear weather, under known amounts of ozone, water vapour and dust in the atmosphere, in different seasons and at different latitudes.

Actual records of the intensity of solar radiation are available at present only for the Central Agricultural Meteorological Observatory at Poona [8]. Proposals for setting up solarigraphs at a network of selected stations in India are at present under consideration.

ESTIMATES OF *q* THE DIRECT SOLAR RADIATION AND OF Q_s THE DIRECT PLUS THE DIFFUSE SKY RADIATION ON A HORIZONTAL SURFACE

Meanwhile, provisional estimates of the total solar radiation received during the day, at a network of 22 selected stations in India, have been worked out for the purpose of our present discussion, for different months of the year. For computing the values of *q*, the amount of radiation from the sun and the sunlit clear sky, per cm.² of a horizontal surface per minute at the ground surface, we have used the isopleths of *q* already computed by Fritz [3] for different values of the precipitable water vapour and air masses corresponding to the different hours of the day at the selected stations, and for the middle of each of the months of the year. From curves showing the computed diurnal variation of *q*, it is easy to estimate by integration, the total mean daily radiation Q_s for cloudless skies in different months of the year. The values of Q_s are given in Table 1. It should be noted that they represent the possible receipt of energy from the sun and the sunlit sky on a clear dustless day, by unit area of a horizontal surface.

ESTIMATES OF q_o, THE INTENSITY OF DIRECT SOLAR RADIATION, THE ENERGY RECEIVED PER MINUTE PER CM.² OF A SURFACE HELD ALWAYS PERPENDICULAR TO THE SOLAR RAYS

The values of Q_s referred to in the earlier section give the solar energy received from the sun and the sunlit sky by a horizontal surface; *q* and Q_s determine the thermal balance at the surface of the ground and of other horizontal surfaces exposed to the radiation from

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[1] The figures in brackets refer to the bibliography on page 197.

TABLE 1. Total solar and sky radiation, Q_o in gm. cal./cm.^{2}/day

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Annual*
Trivandrum	653	692	749	775	766	749	758	767	752	710	645	628	721
Bangalore	584	650	690	706	703	692	746	704	695	649	631	562	6 668
Madras	649	709	747	764	765	750	749	765	750	709	680	605	720
Dharwar	582	632	701	745	751	732	748	752	717	644	594	562	680
Bombay	553	651	736	789	792	791	795	793	738	661	573	542	701
Poona	554	630	734	756	762	741	755	736	698	632	562	533	675
Sakharnagar	565	648	723	773	785	761	765	762	716	737	576	541	688
Samalkot	580	659	731	771	789	786	783	769	739	662	596	570	703
Ahmedabad	535	618	709	809	811	814	807	785	746	640	558	507	695
Powerkhera	522	602	691	783	783	807	780	768	720	621	547	493	676
Labandhe	550	641	733	779	802	797	781	777	716	647	561	525	693
Karachi	516	591	695	766	786	827	814	795	709	611	531	489	678
Jodhpur	486	574	684	792	810	835	805	770	708	597	507	446	668
Jaipur	471	561	671	777	761	811	793	755	689	594	497	438	652
Allahabad	512	593	699	789	805	827	799	784	698	611	536	470	677
Calcutta	532	617	701	781	784	817	816	800	645	624	557	501	681
Delhi	451	551	662	778	803	827	805	760	693	624	481	421	655
Quetta	384	458	572	671	707	729	707	696	605	544	392	354	568
Lahore	436	539	658	777	847	847	817	768	682	619	453	405	654
Jullundur	430	533	657	774	849	844	812	776	669	617	446	403	651
Peshawar	367	454	612	744	819	835	789	759	636	520	402	336	606
Srinagar	319	402	533	649	711	738	690	660	567	451	356	293	531

the sun and the sky. In some of the problems relating to the utilization of solar energy one has to deal with the energy q_o received as direct solar radiation at a surface always held perpendicular to the sun's rays; q_o can be estimated as

$$q_o = q' \sec \theta,$$

where q' is the intensity of the vertical component of direct solar radiation alone on a horizontal surface and θ is the zenith distance of the sun. From comparative observations of q' and q recorded on clear days Kimball has worked out the ratio (r) of q', the vertical component of the direct radiation, to the total radiation q from the sun and sky falling on a horizontal surface (see Table 150 on page 439 of the *Smithsonian Meteorological Tables*, 1951 edition). Thus

$$q_o = rq \times \sec. \theta$$

Values of the radiation q_o so computed, for different hours of the day for different months and stations in India, are available in the India Meteorological Department.

EFFECTS OF CLOUDS AND THE DURATION OF THE BRIGHT HOURS OF SUNSHINE (d)

So far, we have only considered solar radiation in clear or cloudless skies. Haurwitz [4] estimates the percentage of clear day insolation received for various optical air masses and overcast cloud types as in Table 2.

TABLE 2. Ratio of insolation with overcast skies to insolation with cloudless sky (expressed as percentage)

Optical air mass	*Cloud type*							
	Cirrus	*Cirro Stratus*	*Alto Cumulus*	*Alto Stratus*	*Strato Cumulus*	*Stratus*	*Nimbo Stratus*	*Fog*
1.1	85	84	52	41	35	25	15	17
1.5	84	81	51	41	34	25	17	17
2.0	84	78	50	41	34	25	19	17
2.5	83	74	49	41	33	25	21	18
3.0	82	71	47	41	32	24	25	18
3.5	81	68	46	41	31	24		18
4.0	80	65	45	41	31			18
4.5					30			19
5.0					29			19

When we wish to consider the effect of clouds on the total insolation Q_o during an entire day, it is possible to correlate the insolation on cloudy days with the duration (d) of bright sunshine as recorded by the duration of the burns on the charts of a sunshine recorder of the Campbell-Stokes type. Fortunately, records for the duration (d) of bright sunshine are now available in India for a network of 18 stations of the India Meteorological Department, and 25 stations maintained by the Agricultural Departments at Farm Observatories in the states of India.

Quetta in Pakistan has the longest duration of bright sunshine throughout the year. West Punjab (Pakistan) and Punjab (India), the western United Provinces and Rajasthan come next in order, the monsoon months July and August being the only months when the duration of cloudiness is more than 50 per cent of the day. Sind in Pakistan and Bombay Deccan in India come next. July and August in Sind and July to September in Bombay Deccan are the months with duration of sunshine less than 50 per cent of the possible. In south-east Madras, the effect of the south-west monsoon is seen only in the month of July, all the other months having more than 50 per cent of the possible duration. Konkan, Malabar and Bengal are areas in which the period June to September has, generally speaking,

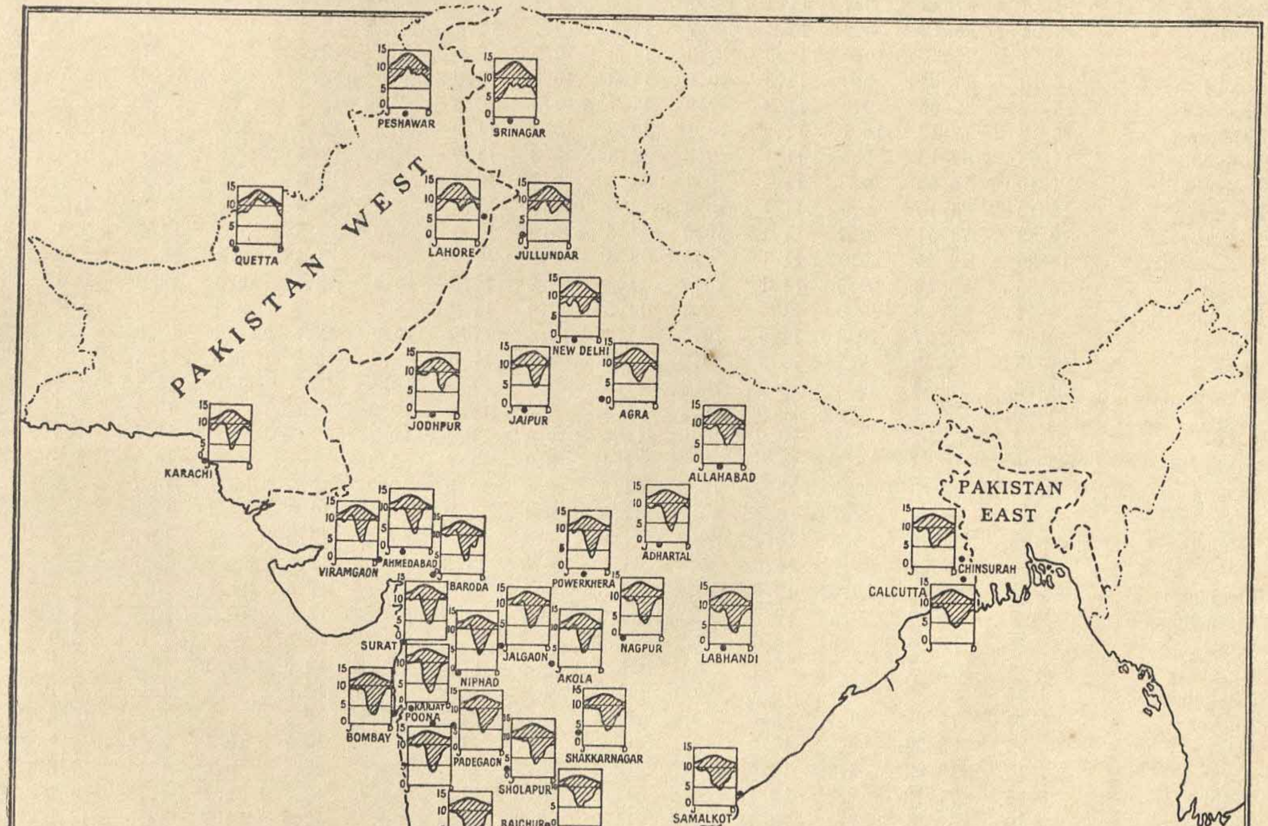

Fig. 2. Mean daily duration in hours of "possible" and "actual" bright sunshine at different stations in India (for the different months of the year). The hatched portions, viz. the difference between the possible and the actual durations, represent the duration of clouds obscuring solar radiation.

TABLE 3. Mean daily actual *(d)* and possible (N) hours of bright sunshine

Station	*Lat.*	*Long.*	*January*		*February*		*March*		*April*		*May*		*June*	
	N	E	*d*	N	*d*	N	*d*	N	*d*	N	*d*	N	*d*	N
	° ′	° ′												
Trivandrum	08–29	76–57	8.4	11.7	8.3	11.9	8.4	12.1	6.1	12.3	7.2	12.5	3.9	12.6
Koilpatti	09–12	77–53	7.3	11.7	8.1	11.8	9.3	12.0	7.3	12.3	7.9	12.5	6.9	12.6
Kodaikanal	10–14	77–28	7.9	11.6	8.4	11.8	8.5	12.0	7.4	12.3	7.5	12.3	5.3	12.7
Pattambi	10–48	76–12	9.9	11.5	9.6	11.7	9.4	12.0	8.5	12.3	8.3	12.6	4.2	12.8
Coimbatore	11–00	76–55	8.4	11.5	8.9	11.7	9.6	12.0	8.4	12.3	8.4	12.6	5.8	12.8
Aduthurai	11–01	79–32	7.7	11.5	8.7	11.7	10.1	12.0	8.6	12.3	8.9	12.6	7.7	12.8
Bangalore	12–58	77–35	8.7	11.4	8.7	11.7	9.7	12.0	8.8	12.4	7.9	12.7	5.2	12.9
Madras	13–04	80–15	8.9	11.4	9.7	11.7	10.1	12.0	9.5	12.4	8.5	12.7	6.6	12.9
Babbur	13–57	76–37	10.0	11.3	10.3	11.8	10.7	12.0	9.7	12.4	10.1	12.7	7.0	13.0
Hagari	15–10	77–04	9.9	11.3	10.2	11.8	10.2	12.0	9.6	12.6	8.8	12.8	6.5	13.0
Dharwar	15–27	75–00	9.7	11.3	9.8	11.7	9.7	12.0	8.4	12.5	7.8	12.8	3.9	13.0
Raichur	16–12	77–12	10.1	11.2	10.1	11.5	10.3	11.9	9.8	12.4	8.6	12.8	5.4	13.1
Samalkot	17–03	82–13	9.8	11.1	9.8	11.5	9.2	11.9	9.6	12.4	9.1	12.9	5.9	13.1
Sholapur	17–40	76–00	9.8	11.1	9.7	11.5	9.9	11.9	9.2	12.5	9.2	12.9	5.7	13.2
Pedegaon	18–12	74–10	9.7	11.1	10.2	11.5	9.9	11.9	9.6	12.5	10.2	12.9	7.0	13.2
Poona	18–32	73–51	9.7	11.1	10.2	11.5	10.0	11.9	9.6	12.5	10.2	13.0	6.6	13.3
Sakharnagar	18–39	77–45	9.5	11.1	9.5	11.5	9.3	11.9	9.3	12.5	9.3	13.0	6.2	13.3
Karjat	18–55	73–18	9.8	11.1	10.0	11.5	10.2	11.9	10.4	12.5	10.8	13.0	5.6	13.3
Bombay	18–54	72–40	9.0	11.1	9.3	11.5	9.0	11.9	9.1	12.5	9.3	13.0	5.0	13.3
Niphad	20–06	74–07	10.3	11.0	10.7	11.4	10.4	11.9	10.2	12.5	11.2	13.0	7.7	13.3
Akola	20–45	77–00	9.9	10.9	10.2	11.4	9.7	11.9	9.9	12.5	10.8	13.1	7.8	13.4
Jalgaon	21–03	75–34	10.1	10.9	10.3	11.4	9.9	11.9	10.4	12.5	11.0	13.1	7.4	13.4
Nagpur	21–09	79–07	9.6	10.9	9.5	11.4	9.0	11.9	9.0	12.5	9.2	13.1	5.4	13.4
Surat	21–12	72–52	9.9	10.9	10.5	11.4	9.8	11.9	10.7	12.5	11.1	13.1	7.6	13.4
Labhandi	21–20	81–45	9.3	10.9	9.1	11.4	8.3	11.9	8.4	12.5	9.0	13.1	5.8	13.4
Baroda	22–18	73–15	9.7	10.9	10.3	11.3	9.5	11.9	10.3	12.5	11.4	13.1	7.9	13.5
Powerkhera	22–50	78–00	9.7	10.8	10.0	11.3	9.1	11.9	10.1	12.6	10.2	13.2	7.3	13.5
Calcutta	22–32	82–20	8.6	10.8	8.7	11.3	8.9	11.9	9.0	12.6	8.7	13.2	5.4	13.5
Chinsura	22–52	88–25	9.1	10.8	9.5	11.3	9.0	11.9	9.7	12.6	9.7	13.2	5.5	13.5
Virangam	23–02	72–07	10.0	10.8	10.2	11.3	9.1	11.9	10.9	12.6	11.1	13.2	9.8	13.5
Ahmedabad	23–02	72–35	9.6	10.8	10.2	11.3	9.7	11.9	10.5	12.6	10.4	13.2	8.3	13.5
Adartal	23–05	79–56	8.8	10.8	9.1	11.3	8.7	11.9	9.4	12.6	9.3	13.2	5.9	13.5
Karachi	24–53	67–07	9.0	10.7	8.7	11.2	9.5	11.9	10.2	12.6	10.3	13.3	7.1	13.7
Allahabad	25–26	81–50	8.1	10.7	9.1	11.2	8.5	11.9	9.9	12.6	9.9	13.3	7.1	13.7
Jodhpur	26–18	73 01	8.9	10.6	9.4	11.2	9.2	11.9	9.9	12.7	11.0	13.3	10.0	13.7
Jaipur	26–55	75–50	8.6	10.6	9.1	11.1	9.7	11.9	9.9	12.7	10.1	13.4	7.7	13.8
Agra	27–10	78–02	8.7	10.6	8.9	11.1	9.5	11.9	10.1	12.7	9.8	13.4	7.8	13.8
Delhi	28–35	77–12	7.7	10.4	8.2	11.1	8.2	11.8	8.7	12.7	9.2	13.5	7.9	14.0
Quetta	30–10	67–01	7.2	10.4	8.3	11.0	8.2	11.8	8.7	12.7	10.5	13.5	11.8	14.1
Jullundur	31–25	75–35	6.5	10.2	7.9	10.9	7.2	11.8	9.7	12.8	10.1	13.7	9.4	14.2
Lahore	31–35	74–20	6.3	10.2	7.6	10.9	8.3	11.8	9.6	12.8	9.8	13.7	9.3	14.2
Peshawar	34–01	71–35	5.6	10.0	6.3	10.8	7.0	11.8	7.8	12.9	9.3	13.8	10.2	14.4
Srinagar	34–05	74–15	3.7	10.0	3.8	10.8	4.7	11.8	6.8	12.9	8.2	13.8	7.9	14.1

less than 50 per cent of the possible duration of bright sunshine. The hilly regions of the south as represented by Kodaikanal are places where clouds obscure the sun for more than half the day during June to November. In the extreme north, the first four months of the year are cloudy, owing to the incidence of the western disturbances; cloudiness revives again in July and August during the south-west monsoon.

Over the greater part of India, bright sunshine exceeds 50 per cent of the possible duration during January to May and again from October to December. In other words, the monsoon season, June to September, is the period when clouds obscure the sun and continuous sunshine cannot be expected except rarely during temporary breaks in the monsoon. It is well known that skies remain overcast for days together in the areas of high rainfall like Malabar, Konkan, Bengal, etc. During the winter and spring months,

Station	*Lat.*	*Long.*	*July*		*August*		*September*		*October*		*November*		*December*		*Annual*	
	N	E	*d*	N	*d*	N	*d*	N	*d*	N	*d*	N	*d*	N	*d*	N
	° ′	° ′														
Trivandrum	08–29	76–57	3.7	12.5	5.9	12.4	5.9	12.2	5.0	12.0	5.5	11.8	8.5	11.7	6.4	12.0
Koilpatti	09–12	77–53	6.3	12.6	6.7	12.5	8.1	12.2	5.9	12.0	6.9	11.7	7.6	11.6	7.4	12.0
Kodaikanal	10–14	77–28	2.9	12.7	4.3	12.5	5.2	12.2	4.3	12.0	5.2	11.7	7.7	11.6	6.2	12.0
Pattambi	10–48	76–12	3.9	12.7	5.1	12.5	7.7	12.2	6.3	11.9	8.3	11.7	9.8	11.5	7.6	12.0
Coimbatore	11–00	76–55	4.5	12.7	6.6	12.5	7.4	12.2	6.6	11.9	6.8	11.7	8.4	11.5	7.5	12.0
Aduthurai	11–01	79–32	6.7	12.7	6.9	12.5	7.9	12.2	5.9	11.9	6.8	11.7	7.5	11.5	7.8	12.0
Bangalore	12–58	77–35	3.4	12.8	5.0	12.6	5.4	12.3	5.6	11.9	7.5	11.6	8.4	11.4	7.0	12.0
Madras	13–04	80–15	5.1	12.8	5.3	12.6	6.7	12.3	6.5	11.9	7.0	11.6	8.5	11.4	7.7	12.0
Babbur	13–57	76–37	4.8	12.9	5.6	12.7	6.8	12.4	6.7	11.9	10.0	11.7	8.3	11.3	8.3	12.0
Hagari	15–10	77–04	5.1	13.0	6.4	12.7	6.8	12.5	6.8	11.9	9.9	11.5	9.7	11.3	8.3	12.0
Dharwar	15–27	75–00	2.1	13.0	3.6	12.7	5.3	12.4	6.1	11.9	9.3	11.5	9.7	11.3	7.1	12.0
Raichur	16–12	77–12	4.9	13.0	6.0	12.7	6.1	12.3	7.5	11.9	9.8	11.4	9.8	11.2	8.2	12.0
Samalkot	17–03	82–13	5.4	13.1	4.4	12.8	5.1	12.3	6.8	11.9	9.0	11.4	9.5	11.1	7.8	12.0
Sholapur	17–40	76–00	3.4	13.1	4.2	12.8	5.3	12.3	7.6	11.8	10.2	11.4	10.1	11.1	7.9	12.0
Pedegaon	18–12	74–10	3.9	13.1	5.8	12.8	6.7	12.3	8.0	11.8	9.9	11.4	9.7	11.1	8.2	12.0
Poona	18–32	73–51	3.3	13.2	3.5	12.9	6.1	12.3	7.7	11.8	9.6	11.3	9.5	11.0	8.0	12.0
Sakharnagar	18–39	77–45	3.6	13.2	4.1	12.9	5.6	12.3	7.5	11.8	9.7	11.3	9.3	11.0	7.2	12.0
Karjat	18–55	73–18	2.7	13.2	2.5	12.9	5.9	12.3	7.5	11.8	9.9	11.3	9.9	11.0	8.0	12.0
Bombay	18–54	72–40	3.1	13.2	2.5	12.9	5.4	12.3	7.7	11.8	9.7	11.3	9.6	11.0	7.4	12.0
Niphad	20–06	74–07	3.8	13.3	4.5	12.9	6.8	12.3	8.9	11.8	10.4	11.3	10.2	10.9	8.8	12.0
Akola	20–45	77–00	4.0	13.3	4.5	12.9	7.0	12.3	8.7	11.7	10.3	11.2	9.9	10.9	8.5	12.0
Jalgaon	21–03	75–34	4.1	13.3	4.7	12.9	6.9	12.3	9.6	11.7	10.2	11.2	10.1	10.9	8.7	12.0
Nagpur	21–09	79–07	3.1	13.3	3.0	12.9	6.3	12.3	8.1	11.7	9.7	11.2	9.2	10.9	7.6	12.0
Surat	21–12	72–52	4.5	13.3	4.1	12.9	7.7	12.3	9.9	11.7	10.1	11.2	10.0	10.9	8.8	12.0
Labhandi	21–20	81–45	3.6	13.3	2.8	12.9	6.1	12.3	8.0	11.7	8.9	11.2	9.3	10.9	7.4	12.0
Baroda	22–18	73–15	4.6	13.4	3.5	13.0	7.8	12.4	6.9	11.7	10.3	11.2	9.9	10.8	8.5	12.0
Powerkhera	22–50	78–00	4.1	13.5	4.9	13.0	5.8	12.4	9.4	11.7	10.3	11.1	9.7	10.7	8.5	12.0
Calcutta	22–32	82–20	4.1	13.5	4.1	13.0	5.1	12.4	6.5	11.7	8.3	11.1	8.4	10.7	7.1	12.0
Chinsura	22–52	88–25	4.5	13.5	5.1	13.0	6.3	12.4	7.2	11.7	8.5	11.1	8.9	10.7	7.7	12.0
Virangam	23–02	72–07	5.4	13.5	4.2	13.0	8.9	12.4	10.2	11.7	10.3	11.1	10.1	10.7	9.2	12.0
Ahmedabad	23–02	72–35	4.6	13.5	3.6	13.0	7.7	12.4	10.1	11.7	10.4	11.1	9.8	10.7	8.7	12.0
Ardatal	23–05	79–56	3.7	13.5	2.7	13.0	6.4	12.4	8.9	11.7	9.3	11.1	8.6	10.7	7.6	12.0
Karachi	24–53	67–07	3.8	13.6	4.2	13.1	7.5	12.4	9.7	11.7	9.3	11.0	8.8	10.6	8.2	12.0
Allahabad	25–26	81–50	5.7	13.6	4.8	13.1	6.7	12.4	9.0	11.7	9.3	11.0	9.2	10.6	8.1	12.0
Jodhpur	26–18	73–01	6.6	13.7	5.7	13.2	8.0	12.4	9.8	11.7	10.0	11.0	9.2	10.5	9.0	12.0
Jaipur	26–55	75–50	4.6	13.8	4.7	13.2	7.4	12.5	10.1	11.7	9.9	10.9	9.0	10.5	8.4	12.0
Agra	27–10	78–02	6.0	13.8	5.6	13.2	7.7	12.5	9.9	11.7	9.5	10.9	8.5	10.5	8.5	12.0
Delhi	28–35	77–12	6.0	13.9	6.3	13.3	6.9	12.5	9.4	11.6	8.7	10.8	8.3	10.3	8.0	12.0
Quetta	30–10	67–01	11.0	14.0	10.0	13.4	11.5	12.5	11.2	11.6	8.9	10.7	7.5	10.2	9.6	12.0
Jullundur	31–25	75–35	6.8	14.1	7.3	13.5	8.4	12.5	9.5	11.6	8.6	10.6	7.6	10.1	8.3	12.0
Lahore	31–35	74–20	7.2	14.1	8.2	13.5	9.0	12.5	9.7	11.6	9.0	10.6	7.3	10.1	8.4	12.0
Peshawar	34–01	71–35	8.9	14.3	8.9	13.6	8.6	12.5	8.8	11.5	8.1	10.5	6.3	9.9	8.0	12.0
Srinagar	34–05	74–15	8.5	14.3	7.6	13.6	8.3	12.5	8.3	11.5	7.5	10.5	2.9	9.9	6.5	12.0

sunshine is above 70 per cent of the possible duration over practically the whole country and attempts to utilize solar energy directly for practical purposes are likely to be most successful during those seasons.

UTILIZATION OF SOLAR RADIATION

PHOTOSYNTHESIS

Photosynthesis is the process by which plants, with the aid of the chlorophyll pigment, utilize the energy of solar radiation to produce carbo-hydrates out of water and carbon dioxide. It is found that photons of all colours, red, green or blue, which are absorbed are equally effective in photosynthesis. One gramme of carbon in carbo-hydrates so produced evolves when burnt 112 kil. cal., which is the minimum energy necessary for the production of 1 gr. atom of carbon by photosynthesis. There are 6.02×10^{23} atoms of carbon in 1 gr. atom, and at the rate of 1 quantum of light of wave-length say, 6,000 A.U., as being necessary for the formation of each carbon atom by photosynthesis, the total energy so utilized will be of the order of:

$$
\begin{aligned}
& 6.02 \times 10^{23} \times h\gamma \\
&= 6.02 \times 10^{23} \times 6.62 \times 10^{-27} \times 5 \times 10^{14} \text{ erg.} \\
&= \frac{6.02 \times 10^{23} \times 6.62 \times 10^{-27} \times 5 \times 10^{14} \text{ gr. cal.}}{4.18 \times 10^{7}} \\
&= 48 \text{ kil. cal.}
\end{aligned}
$$

[where h Planck's constant is 6.62×10^{-27} erg. sec. and γ for $\lambda = 6{,}000$ A.U. is equal to 5×10^{14}]

Laboratory investigations referred to by F. Daniels [2] indicate that 8 quanta of radiation are necessary for fixing each carbon atom, so that the energy trapped for fixing 1 gr. atom of carbon in photosynthesis is of the order of: 48 × 8 or 384 kil. cal., while only 112 kil. cal. are actually utilized. The efficiency of photosynthesis even under the most favourable laboratory conditions is therefore of the order of $\frac{112}{384}$ or 30 per cent.

We may now consider the actual utilization of solar radiation by field crops in India. Let us assume that 1 cm.^{2} of land receives on an average about 500 gr. cal. per day. At this rate the solar radiation received per acre is of the order of $42{,}000 \times 30^2 \times 500$ or about 18.9 million kil. cal. per day. Neglecting the ultraviolet and infra-red and assuming that only half of solar radiation is effective in photosynthesis, and assuming an efficiency of a third, we have about 3 $^1/_6$ million kil. cal. actually available for effective photosynthesis per acre per day.

Organic material like wood, etc., yields about 3 $^1/_2$ million kil. cal. per ton and we may consider what is the actual tonnage of dry matter yielded by crops per acre and compare the energy produced by burning this quantity with the total radiation received during the average life of the crop.

TABLE 4

Crop	*Approximate yield of dry matter per acre*	*Average duration of the growing season*	*Percentage of total solar radiation received during growing season actually utilized*
	tons		
Wheat	3	120 days	0.44
Paddy	8	120 days	1.17
Jowar	12	120 days	1.76
Sugar cane	40	12 months	2.0

It is clear that 1 ton of dry matter can be produced in one day if all the solar energy of some 3 $^1/_6$ million kil. cal. stored for photosynthesis per day is fully utilized, as this is nearly equal to the 3 $^1/_2$ million kil. cal. evolved per ton on burning. Actually we get up to 40 tons in the case of sugar cane after a growth of 365 days, when the energy stored will be 365×3 $^1/_6$ million kil. cal. The actual photosynthetic efficiency of ordinary agriculture is thus only about 2 per cent in the case of a heavy crop like sugar cane and smaller percentages in the case of other crops.

We have, therefore, much unutilized solar energy which could be geared to increased production of food. As algae are more efficient than plants in utilizing ti for photosynthesis, many investigations for evolving edible algae, etc., are now under way in some of the laboratories of the world.

CONTRIBUTION TO THE THERMAL BALANCE OF THE GROUND

The solar radiation which fails to be intercepted by growing plants, actually warms the soil surface and raises its temperature up to as high as 70° C. in some parts of India during the clear season. The desiccating and sterilizing effect of such high surface temperatures have been reported to be beneficial to the next crop. Solar energy can be used for evaporating and concentrating salt pans in the salt producing areas. Besides such minor uses, the heating up of the soil and the conduction and convection of this heat into the atmosphere is responsible for the large scale, as well as small scale, atmospheric circulations. The utilization of wind energy and of the waves on the sea raised by the winds, etc., is another aspect of the energy problem.

OTHER TECHNICAL UTILIZATION OF SOLAR ENERGY

Solar heating as such can be used for domestic purposes, refrigeration, etc., and in running various types of "solar engines" where the solar energy is concentrated by mirror systems driven by clockwork so as to be always facing the sun. Descriptions of some of these devices are already available in the literature [1, 6], and it is hoped that other contributors to the symposium who may be actually engaged in developing solar engines will be presenting the latest results on this aspect of the problem. For ensuring a worthwhile efficiency in such machines the problems of minimizing heat losses by conduction, convection and radiation assumes enormous importance.

CONCLUDING REMARKS

We have in this paper presented some of the relevant solar radiation data partly observed, partly computed, for different parts of India. It is hoped that, until more reliable data based on detailed observations are

TABLE 5. Actual solar and sky radiation Q in gm. cal./cm.^{2}/day

Station	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Annual*
Trivandrum	561	533	577	504	536	405	402	491	481	440	413	503	487
Bangalore	473	520	580	544	513	408	381	416	431	415	473	450	467
Madras	526	610	643	626	581	495	442	467	510	489	489	473	530
Dharwar	506	544	588	604	541	388	336	398	437	425	497	489	480
Bombay	464	547	596	631	626	459	358	373	457	496	499	477	499
Poona	488	561	631	620	632	489	378	375	475	474	489	464	506
Sakarnagar	491	557	622	626	620	487	390	389	444	465	501	465	505
Samalkot	516	573	636	632	615	478	470	431	429	463	495	496	520
Ahmedabad	476	556	596	696	673	586	452	408	545	557	513	462	543
Powerkhera	470	536	567	681	642	549	413	369	497	521	503	449	516
Labhandi	418	538	572	592	618	486	399	373	465	492	466	457	490
Karachi	444	491	583	643	645	554	423	437	510	513	462	420	511
Jodhpur	418	522	561	657	697	668	523	470	531	513	461	393	534
Jaipur	382	476	570	650	616	560	436	423	489	517	447	381	495
Allahabad	415	480	546	655	644	570	488	485	475	501	467	414	511
Calcutta	442	506	568	617	682	482	416	441	387	431	445	415	486
Delhi	361	441	509	599	610	571	491	486	478	524	442	353	489
Quetta	280	371	440	576	579	627	587	578	551	511	337	283	472
Lahore	319	420	513	630	661	635	539	553	539	532	394	320	505
Jullundur	314	421	473	627	679	641	528	535	509	524	374	323	496
Peshawar	253	318	434	536	622	651	576	570	489	421	329	249	454
Srinagar	185	225	315	435	505	509	490	455	425	357	278	155	361

recorded at a network of stations, these provisional data may prove useful to scientists in India who wish to use solar radiation for practical purposes. The limitations to such use, set by the rather low efficiencies of the various processes, such as photosynthesis in nature and various man-made devices, and the seasonal uncertainties of the availability of solar energy have also been discussed briefly.

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L'ÉNERGIE SOLAIRE EN INDE

par

L. A. RAMDAS et S. YEGNANARAYANAN

RÉSUMÉ

Les auteurs résument les calculs sur lesquels se fonde l'équation de Bouger, qui donne le facteur global de transmission du rayonnement solaire. Après correction pour absorption due à l'ozone, les valeurs de T permettent de calculer le rayonnement solaire reçu à la surface de la terre par temps clair, en présence de quan-

tités connues d'ozone, de vapeur d'eau et de poussières atmosphériques, aux différentes saisons et sous différentes latitudes.

L'intensité du rayonnement solaire n'est actuellement enregistrée en Inde qu'à l'Observatoire central d'agronomie de Poona, mais on se propose de doter le pays d'un réseau de pyrhéliographes.

Toutefois, les valeurs du rayonnement moyen quotidien (Q_o) pour un ciel sans nuages et pour différents mois de l'année ont pu être estimées : le tableau 1 montre la quantité d'énergie que fournit la radiation directe et diffuse, par temps clair et sans poussières, par unité de surface d'un plan horizontal.

Il suffit parfois de connaître l'énergie reçue (Q_o) du rayonnement solaire direct. Les auteurs indiquent le mode de calcul.

Ils étudient également l'effet de la nébulosité telle qu'elle se présente en Inde. Sur la plus grande partie du territoire de ce pays, la durée d'ensoleillement dépasserait 50 % des heures diurnes de janvier à mai et d'octobre à décembre.

Après quelques considérations générales sur la photosynthèse les auteurs traitent de l'influence du rayonnement solaire sur les cultures en Inde ainsi que du rôle du rayonnement solaire dans l'équilibre thermique du sol et évoquent rapidement divers autres emplois possibles de cette forme d'énergie.

ENERGÍA SOLAR EN LA INDIA

por

L. A. Ramdas y S. Yegnanarayanan

RESUMEN

Los autores resumen los cálculos que llevaron a la ecuación de Bouger para la transmisión combinada de la radiación solar. Los valores de $T\lambda$, una vez corregidos teniendo en cuenta la absorción debida al ozono, permiten calcular la radiación solar que llega a la superficie de la tierra en un día despejado, en presencia de cantidades conocidas de ozono, de vapor de agua y polvo en la atmósfera, en diferentes estaciones y en diferentes latitudes.

La intensidad de la radiación solar sólo se registra hoy en la India en el Observatorio Agrícola Central de Poona, aunque se tiene el propósito de establecer por todo el país una red de solarígrafos.

No obstante. se han calculado los valores de Q_o (radiación media diaria) con cielos despejados en diferentes meses del año. La tabla 1 muestra la cantidad de energía que es posible recibir del sol (directa) y de un cielo con sol en un día despejado y sin polvo en suspensión (indirecta), por metro cuadrado de superficie horizontal.

Algunas veces basta conocer la energía (q_o) recibida como radiación solar directa. Los autores indican el procedimiento para dicho cálculo.

El efecto de las nubes es también objeto de examen, particularmente por lo que se refiere a la India. En la mayor parte del país se calcula que la duración de insolación sobrepasa en un 50 % la duración posible de enero a mayo y de octubre a diciembre.

Después de tratar de manera general la cuestión de la fotosíntesis, los autores examinan la influencia de la radiación solar en los cultivos de la India. Luego tratan de la aportación de la radiación solar al equilibrio térmico del suelo y se ocupan de otras aplicaciones de la energía solar.

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DISCUSSION

Mr. **Chinapper.** Dr. Ramdas and Mr. Yegnanarayanan have mentioned the use of solar energy in the production of salt from sea brine. This method of salt production is very ancient, but it is only very recently that an analytical study of the solar evaporation of sea brine has been attempted in Israel and Australia. The first paper on the subject I am aware of is that by C.W. Bonythou of Australia which appeared in 1950. At present an investigation of this problem is being done in Ceylon by D. N. Selvaratram and myself.

Investigators of evaporation have chosen two methods of attack. Penman and Rohwer for example have obtained equations taking into account the difference between the vapour pressure of the brine solution and the atmosphere, and the wind velocity, while Sutton and others have suggested equations taking into account only atmospheric turbulence while giving the pressure conditions at the brine-air interface. It seems at present that neither of these methods quite fits the conditions. The second method seems to be unsuitable because it cannot account for condensation, and the first method because it ignores the effect of temperature. And temperature is precisely the factor we must take into account if it is increased by a more efficient use of solar radiation, either by the use of dyes—a green dye seems most suitable at present—or by some other method.

The investigation we are engaged on is being conducted in two stages: (a) controlled experiments to study the evaporation from tanks under measured conditions of wind velocity, humidity, air and brine temperatures, and solar irradiation; and (b) correlation of the results of the first stage with measurements made in a specially controlled evaporating area at the salterns of the Salt Department of the Government of Ceylon at Elephant Pass.

Mr. **Bleksley.** This conference is not, of course, in a position to make recommendations. I would nevertheless like to support Dr. Ramdas' plea for an extension of solar radiation programmes to other arid regions of the world. Dr. Black's paper shows clearly how little we really know about radiation in those regions where solar energy is likely to prove of greatest value. It is clearly not enough to develop methods of utilizing solar energy; at the same time we should attempt to obtain the detailed information which will enable us to decide where these methods could be applied to the greatest advantage.

A BRIEF RESUME OF WORK ON SOLAR ENERGY DEVELOPMENT AT THE NATIONAL PHYSICAL LABORATORY OF INDIA

by

K. N. MATHUR and M. L. KHANNA

During the last three years the laboratory has been engaged on projects for the utilization of solar energy which it is our purpose to summarize in this paper. Sunshine hours in Delhi exceed 2,500 annually, and reach 2,800 in certain years. This gives better than 60 per cent of the total possible sunshine period. The highest percentage occurs from the middle of September to the middle of April. June, the hottest month, has the smallest number of sunshine hours mostly because of the presence of fine dust in the atmosphere. Though these weather conditions hold only for the region around Delhi, they apply approximately to the whole of northern India, excluding the hilly tracts.

The laboratory has been interested in the development of processes depending on direct utilization of solar energy either through mirrors or solar absorbers. These processes could be adopted for the following purposes: (a) domestic cooking and water heating; (b) lift-irrigation; (c) water distillation; and (d) air conditioning and refrigeration.

To meet the requirements of (a), the laboratory undertook the development of a cheap solar cooker [1][1] which has attracted considerable attention. This is a concave mirror made of aluminium with a polished anodized surface about 9.6 ft.^{2} in area. A domestic water heating arrangement has also been set up; its performance forms the subject matter of a separate paper.

The solar cooker suffers from the limitation that it can only be used during hours of bright sunshine. Thus the cooking of early morning breakfast is excluded. It is capable of cooking a lunch and under favourable conditions some part of the dinner; used with a pressure cooker the cooking time can be cut very considerably. It has been used regularly with a small steam cooker with three compartments. Most of the vegetables can be cooked completely in about 35 to 40 minutes. If used with reasonable care the anodized aluminium is fairly resistant to atmospheric corrosion. The standard size of the cooker with an effective surface area of 9.6 ft.^{2} is capable of giving the heat equivalent of a 350 watt electric hot plate during the middle part of the day. Larger sizes of mirrors could be produced, but only by sacrificing portability and ease of manipulation for focusing. Design of special utensils for use with the cooker is desirable, since only the bottom of the utensil receives energy. It is consequently advantageous to shield the sides with insulating material. This greatly reduces convection losses, which become quite marked on a windy day.

The cooker has a great future in the villages of India, but since the first cost is high there is no immediate chance of its finding its way into peasant homes. If it could, then there is the possibility of saving cow dung for use as manure instead of fuel, thus leading to greatly increased soil fertility.

The cooker can be used in arid regions where no fuel is available. It was recently tried in Somaliland where it could utilize up to 900 B.Th.U. (equivalent of 265 watts of electric energy). Since the total solar radiation there is 2,817 B.Th.U./hour, the ratio of utilized energy of the total is 33 per cent.

One of the main requirements of the Indian farmer is a source of energy for lift-irrigation. In most parts of north India artesian wells could be sunk; the water table is from 15 to 50 ft. below the ground surface. In the arid regions of Rajasthan the water may be as much as 100 ft. below the surface. It is clear that even a small pumping unit can be very useful for the village economy. This will help irrigation not only from wells but also from rivers and tanks.

The problem has been studied from two angles: the manufacture of large concave paraboloidal mirrors capable of producing an energy output of about 1.5-2 kw.; and plane mirrors, such as those described in the paper by Gardner, whereby heat gathered from between 100 to 200 individual plane mirrors is brought to a common focus and concentrated on a boiler to raise steam.

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[1] The figures in brackets refer to the bibliography on page 201.

A small boiler unit has been designed at this laboratory. The underside is dome-shaped, to act as a receiver of energy. This special shape has been designed to ensure as near to black-body conditions as possible. The boiler has a capacity of four gallons of water. The quantity of heat likely to be available in Gardner's plane mirror unit is estimated at 20,000 B.Th.U./hour. This should be capable of raising 20 lb. of dry and saturated steam, at 250° F. and a pressure of 30 lb./in.^{2} absolute per hour, using feed water at 90° F.

A concave mirror with an effective aperture of 28.3 ft.^{2} has been installed. A design is in hand for making a hot air engine. The design of hot air engines has been examined in some detail by H. Rinia and F. L. Van Weenen [3] in a series of papers published in the *Philips Technical Review*. The correct design of the heat interchanger system is shown to be important.

If it is possible to design such an engine with an efficiency figure of 15-20 per cent it would perhaps be the most important type of solar energy utilization. We had under observation a small hot air engine made from an old kerosene-operated fan. With a mirror aperture of 12.6 ft.^{2} effective this unit develops about 1/20 h.p.

Certain parts of the arid regions of Rajasthan suffer from acute water difficulty: the water available from wells contains a very large percentage of dissolved salt, of which common salt forms the most important part. Although methods making use of ion exchange resins are now possible, they are very expensive and it is doubtful if they will ever become cheap enough. With solar power available, distillation may be effected cheaply and water made available for drinking and cooking purposes.

The problem of using solar energy for domestic refrigeration and air conditioning is being studied in several countries. We have made some preliminary experiments using a solar cooker for heating oil, which is then circulated through a refrigerator of the Electrolux type. This refrigerator depends for its action on the evaporation of ammonia from liquid ammonia. The common Electrolux refrigerator requires a minimum temperature of about 300° C. in the heating unit to give its stated performance. It is possible to heat a suitable liquid at the focus of a concave mirror and then pass this through the heating tube of the refrigerator. Our preliminary results suggest that the Electrolux heating system may need considerable change before it can be adopted for use with solar energy.

A concluding word may be said about the use of solar energy in air conditioning. The laboratory has a 250 ton air conditioning plant made by Carrier. We are using this plant as a reversible heat pump. While it supplies cold air to the laboratory during the summer months, it provides warm air during the winter months, with a relative humidity of about 50 per cent. On the warm cycle the cold-producing side of the machine is kept warm by pumping in water at approximately 40,000 gallons per hour. The following data, recorded on 6 January 1954, are typical of the usual winter months in Delhi:

	At 11 a.m.			*At 1.30 p.m.*			*At 4 p.m.*			
	Dry bulb	*Wet bulb*	*Humidity*	*Dry bulb*	*Wet bulb*	*Humidity*	*Dry bulb*	*Wet bulb*	*Humidity*	*Remarks*
	°F.	°F.	%	°F.	°F.	%	°F.	°F.	%	
Outside	61	54	64	66	56	56	62	55	64	Plant started at 9.30 a.m.
Chilled water in	55.5			56.5			57			
Chilled water out	51.5			52.5			55.5			
										Plant stopped at 3.30 p.m. because of rain
Cooling pond water	55			56			56.5			
Well water	79			76			79.5			

In the Carrier plant installed in the National Physical Laboratory of India, the evaporator is designed to cool 800 American gallons/minute of water from 46.5° to 39° F, when the condenser is supplied with 800 gallons per minute of water at 90° F. In the reverse cycle we use the condenser water for taking the heat load of the laboratory. The hot water is pumped to the secondary coolers—15 in number—where the air blowing through finned coils is heated to the required degree of temperature. We have found that for our winter months the best comfort conditions are attained with room temperature 76°-78° F., with 50 per cent humidity, when the outside temperature ranges from 55° F. at 10 a.m. rising to 66° F. at noon. Under these conditions of working the condenser water is delivered to the machine at 96° F., and comes out at 100° F. The evaporation side draws in water at 57° F. which is cooled down to 53° F. Thus on the heating cycle the energy is abstracted from water, circulating at the rate of 38,000 imperial gallons per hour and falling in temperature from 56.5° F. to 52.5° F. (from the figures in the table for 6 January 1954). This gives 1.5 million

B.Th.U. of energy abstracted per hour, and all this energy is derived from the sun through water sprays. We thus utilize 3,088 kwh. of solar energy for laboratory heating. If all this energy were to be derived from electrically heated coils, which is the most common way of heating, we should use electrical energy valued at Rs.240 per day for a working time of seven hours. In a month this comes to Rs.7,200 and for the three winter months when heating is required the total would come to over Rs.21,600.

BREF COMPTE RENDU DES TRAVAUX DU LABORATOIRE NATIONAL DE PHYSIQUE INDIEN SUR L'EXPLOITATION DE L'ÉNERGIE SOLAIRE

par

K. N. Mathur et M. L. Khanna

RÉSUMÉ

Les travaux sur l'énergie solaire effectués au Laboratoire national de physique ont trait à l'exploitation de cette forme d'énergie, par réflexion ou absorption, aux fins suivantes : usages domestiques (cuisine et chauffage de l'eau) ; élévation d'eau pour irrigation ; distillation de l'eau ; conditionnement de l'air et réfrigération.

Pour les deux premiers usages, on a mis au point un four solaire d'un faible prix de revient pourvu d'un concentrateur concave en aluminium traité par oxydation anodique. Cet appareil fournit au milieu de la journée une quantité de chaleur équivalente à celle d'un réchaud de 350 watts.

En ce qui concerne le puisage de l'eau d'irrigation, les essais ont porté sur de grands miroirs paraboliques concaves, capables de faire fonctionner des moteurs à air chaud. On a également conçu une petite chaudière dont la partie inférieure, en forme de dôme, joue le rôle de récepteur. Equipée d'un groupe à miroirs plans (appareil décrit par Gardner dans sa communication), cette chaudière devrait produire 9 kg à l'heure de vapeur sèche à 120° C. sous 2 kg/cm^2 de pression à partir d'eau à 32° C.

L'élaboration d'un moteur à air chaud est également en train.

En ce qui concerne la purification de l'eau salée, on se propose d'utiliser l'énergie solaire pour faire fonctionner un appareil de distillation.

Le laboratoire se sert d'une installation de conditionnement d'air de 250 tonnes comme d'une pompe thermique réversible fournissant de l'air froid pendant les mois d'été et de l'air chaud à 50 % d'humidité relative pendant l'hiver. Les auteurs décrivent le mode de fonctionnement de cette installation et indiquent quelles économies elle permet de réaliser.

BREVE RESUMEN DE LOS PROGRESOS REALIZADOS EN EL ESTUDIO DE LA ENERGÍA SOLAR EN EL LABORATORIO NACIONAL DE FÍSICA DE LA INDIA

por

K.N. Mathur y M.L. Khanna

RESUMEN

Los trabajos sobre la energía solar realizados en el Laboratorio Nacional de Física han versado sobre la utilización de dicha energía, tanto por reflexión como por absorción, con los fines siguientes: cocción de alimentos y calentamiento de agua para fines domésticos; elevación del agua de riego; destilación del agua; acondicionamiento del aire y refrigeración.

Para el primero de esos fines se ha construído una cocina solar barata, utilizando un concentrador cóncavo anodizado. Ese aparato da, al mediodía, el calor equivalente a un hornillo eléctrico de 350 watios.

Para la elevación del agua de riego, prosiguen los experimentos con espejos cóncavos parabólicos capaces de hacer funcionar motores de aire caliente. También se ha construído una pequeña caldera, cuya parte inferior es cupuliforme, que hace las veces de colector. Con un grupo dotado de espejos planos (descritos en el trabajo de Gardner) deberían obtenerse 9 kg hora de vapor seco a 120° C y 2 kg de presión por cm^2 utilizando, para su alimentación, agua a 32° C.

También se trabaja en la construcción de un motor accionado por aire caliente.

Para purificar el agua salobre se propone utilizar la energía solar para el proceso de destilación.

El Laboratorio utiliza su grupo de acondicionamiento de aire de 250 toneladas como bomba de calor reversible, suministrando aire frío en los meses de verano y aire caliente con una humedad relativa de cerca del 50 %, en los meses de invierno. Se describe el método de funcionamiento de ese grupo y su utilidad desde el punto de vista económico.

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SOME OBSERVATIONS ON A DOMESTIC SOLAR WATER HEATER

by

K. N. Mathur and M. L. Khanna

For the utilization of solar energy for human needs, development has proceeded on two different lines. In one, use has been made of lenses or mirrors whereby solar energy falling over a large area has been brought to a focus and high temperatures have thereby been attained over small areas. In the other method, heat collectors have been used in which extended surfaces receiving solar radiations transfer heat to a fluid medium flowing through the collecting unit. This method has the advantage over the other that heat can be stored and used during periods when there is no sun. It has the disadvantage that high temperatures are not possible, though large quantities of the fluid can be heated through a limited range of temperature.

Which method is used depends upon the purpose for which energy is to be utilized. Mirrors up to 25 ft. and more in diameter have been used by Trombe in France, and by workers in the U.S.S.R. and elsewhere, to attain temperatures hitherto regarded as impossible. In general, this method would find application where high temperatures are the objective. For obtaining a fair amount of heat concentration it becomes necessary to have a large collecting area and this makes the cost of installation high. Also because of the movement of the sun, some method of keeping the focal spot at the same point has to be used. In small concave mirrors of the type developed at this laboratory for cooking purposes, it has been possible to make adjustments manually: this can be done at intervals of 10-15 minutes, since the surface to be heated is large enough to permit appreciable movement of the focal point. In the larger installations it has been usual to keep the mirror position fixed and use a large sheet of plane reflectors to direct the sun's rays on to the concave mirror.

The system employing extended heat collectors has the advantage that practically no attention or movement is necessary, and built-in collectors with large areas have made it possible to use this method for heating large houses. In fact whole roofs with a southern aspect have been made up as heat collectors, as in the work of Hottel and his co-workers at the Massachusetts Institute of Technology for solar house heating. With proper methods of insulation the heat has been conserved for use overnight or on cloudy days.

The success of any method of utilizing solar energy inevitably depends upon the number of sun hours available, and since this number is most favourable during the Indian winter season it appeared desirable to develop a type of flat plate heat collector which could be used all through the winter season for supplying the domestic requirements of hot water for a small family. Such installations have been used previously in the U.S.A. and elsewhere, and the entire aim of our present work has been to gather data for the use of a cheap unit under the conditions of the northern Indian winter, which is characterized by clear bright sunny days.

The main characteristics of the Indian winter months are as follows: Beginning with October the temperature starts going down and by about the middle of the month the Delhi maximum (average) falls to 90° F. By the end of November the maximum goes down to 80° F. and the minimum to 45° F. In December and January minima are around 38° F. During February the temperature shows a tendency to rise and March shows a distinct rise. Towards the end of March the hot season has set in and the equinox is in fact a herald of the summer season. An average Indian household needs a domestic supply of hot water for bathing and washing purposes from say the middle of October to the end of February, i.e. for a period of about four and a half months. Table 1 shows that this is about the most favourable period for utilizing solar energy.

EXPERIMENTAL

In the U.S.A. flat plate absorbers have mostly been made by fixing a number of copper pipes between two

TABLE 1. Bright sunshine hours (1952)[1] at New Delhi, latitude 28° 35′ N; longitude 77° 12′ E.

Month	*Nil or trace*	*0.1 to 3 hours*	*3.1 to 6 hours*	*6.1 to 9 hours*	*Above 9 hours*	*Total hours for the month or year*	*Percentage of possible hours of sunshine in the month or year*
January	0	2	3	4	22	263.4	81
February	1	3	2	7	16	227.2	70
March	0	2	4	12	13	240.8	65
April	0	0	4	8	18	254.1	66
May	1	3	5	7	15	239.9	57
June	13	7	3	4	3	91.7	22
July	4	4	6	11	6	182.9	43
August	2	9	7	5	8	164.1	40
September	0	2	1	14	13	245.4	66
October	0	0	1	7	23	288.6	91
November	0	0	0	3	27	287.4	89
December	1	2	6	12	10	224.3	70
Year	22	34	42	94	174	2 709.8	60

[1] Data supplied through the courtesy of India Meteorological Department.

headers, the lower header supplying inlet water which gets heated in its passage through copper tubes. The tubes were generally soldered to the under surface of a large blackened copper sheet which acted as the main receiver of solar energy. This arrangement was placed under 2 or 3 layers of glass panes. This to our mind

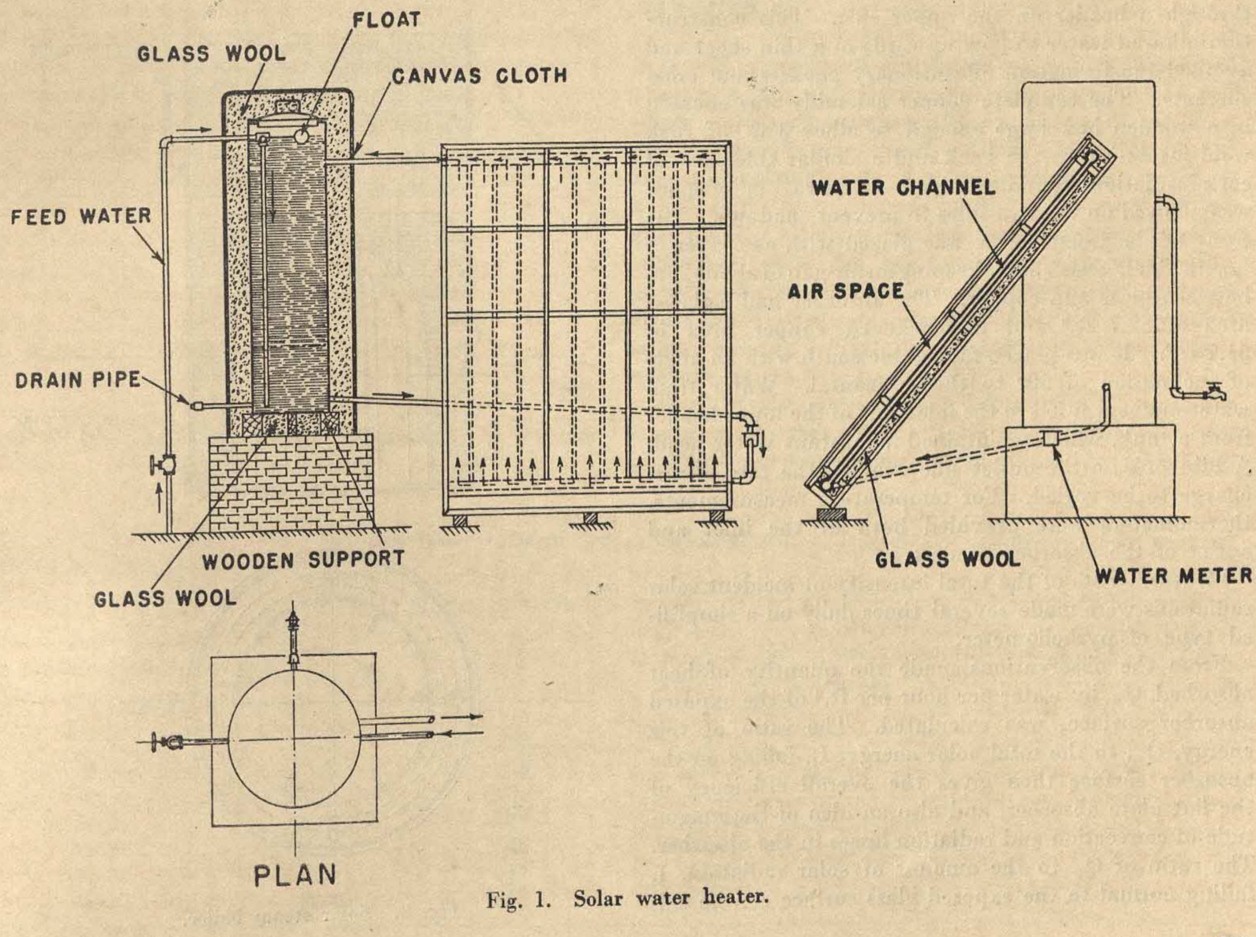

Fig. 1. Solar water heater.

has the disadvantage that since the heat transfer is indirect—in as much as the energy is first absorbed by the sheet and then transferred to neighbouring tubes—the temperature of the copper sheet between the tubes is usually much higher than in the method employed in the present experiments. In these, to avoid heat loss, recourse has been had to several layers of glass. In the present experiments, since water is in direct contact with the sheets, the temperature of the copper sheet is only very slightly higher than that of the water and hence we could avoid making use of multiple glass layers thereby reducing cost and also the difficulty of keeping the lower glass surfaces clean (Fig. 1).

The flat plate absorber is shown diagrammatically in Fig. 2. It was so arranged that water flows slowly in a thin layer between two 18-gauge copper sheets, separated by about $^1/_2$ in. distance. The upper sheet was ribbed as shown in Fig. 1., to stiffen the construction and to provide channels for water to flow upwards. The upper copper surface was thinly coated with carbon black dispersed in shellac-spirit solution. The lower sheet was kept flat and the two were held together at the points of contact by means of suitably spaced rivets. Water was let in through a header soldered to the copper sheets at the lower end, and was let out through a header on the upper side. This construction allowed water to flow upwards in a thin sheet and avoided the formation of stationary pockets and cross currents. The complete copper assembly was encased in a wooden box large enough to allow 3 in. of rock wool insulation at the back and a similar thickness of cork insulation around the sides—an extra 4 in. of space was allowed on the two sides to prevent shadows. The front of the wooden box was glazed with one layer of $^1/_8$ in. thick glass sheet, keeping an air-gap of about 2 in. between glass and copper. The absorber had a glazed area of 58.7 ft.^{2} and a blackened copper area of 51.7 ft.^{2}. It was placed facing due south with an angle of inclination of 50° to the horizontal. Water from water mains was led to the inlet side of the lower header from a tank, which maintained a constant water head. A bib cock on the outlet side enabled the rate of discharge to be varied. For temperature measurements, thermometers were provided both at the inlet and outlet of the absorber headers.

Measurements of the total intensity of incident solar radiations were made several times daily on a simplified type of pyrheliometer.

From the observations made the quantity of heat absorbed, Q_w, by water per hour per ft.^{2} of the exposed absorber surface, was calculated. The ratio of this energy, Q_w, to the total solar energy, I_t, falling on the absorber surface then gives the overall efficiency of the flat plate absorber, and also an idea of the magnitude of convection and radiation losses in the absorber. The ratio of Q_w to the amount of solar radiation, I, falling normal to the exposed glass surface can be calculated from I_t making use of the following equations:

$I = I_t (\sin a . \cos \theta + \cos A . \cos a . \sin \theta)$ in which A is obtained from the relation:

$$\text{Sin } A = \frac{\cos \delta \times \sin h}{\cos a}$$

where:

h = hour angle, i.e. the apparent rotation of the celestial sphere about the earth's axis, measured westwards in degrees from the south meridian, 1 hour = 15°;

δ = solar declination on the particular day, i.e. the angle of sun measured above or below the celestial equator (obtained from solar almanac);

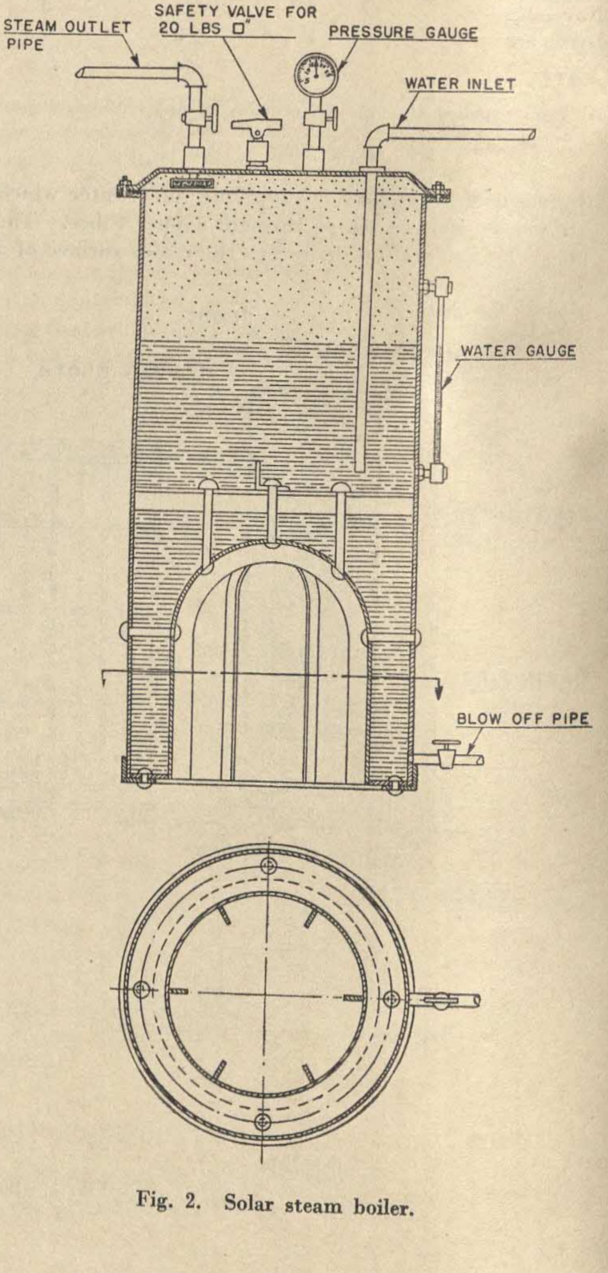

Fig. 2. Solar steam boiler.

a = solar altitude above horizon;
θ = angle of the absorbing surface on the horizontal.

Since in actual domestic use it would be necessary to provide an arrangement for storing hot water, a 100 gallon vertical cylindrical type storage tank was made and connected to the heater. The general lay-out is shown in Fig. 1. The reservoir and the connecting pipes were heavily lagged with glass or rock wool. The arrangement of pipes shown allowed water to circulate and heat up through thermo-syphon action. For use, water is drawn from the top layer where it should have the maximum temperature.

To compare efficiency of absorption of energy, readings were taken without the storage tank. The average heat absorbed by water at different hours of the day during January 1954 is shown graphically in Fig. 3.

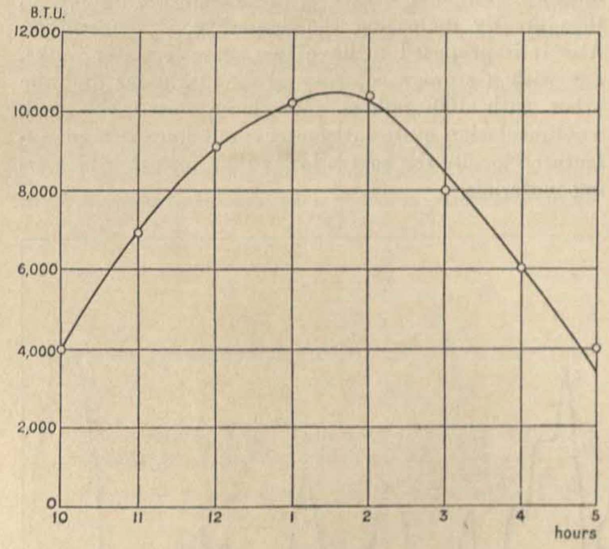

Fig. 3. Average heat absorbed B.Th.U./hour in January 1954.

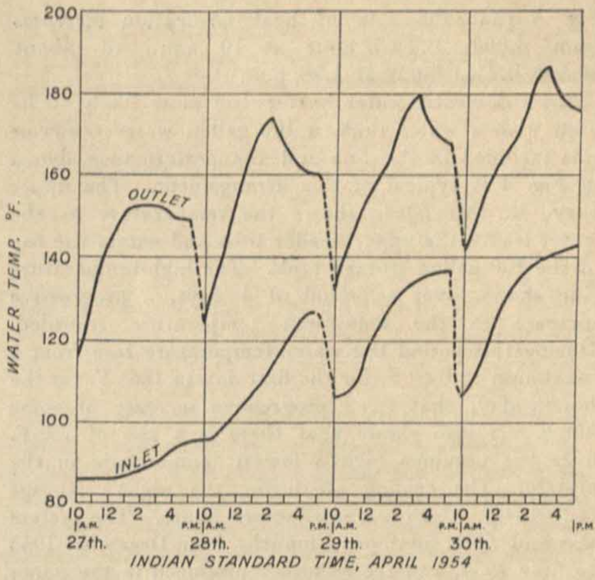

Fig. 4. Progressive increase in temperature of reservoir after first filling.

DISCUSSION

It would appear from the data relating to the absortion of energy that with the arrangement described in this paper a fairly high average efficiency has been attained. The efficiency is low—between 35 and 40 per cent—in the earlier and later parts of the day when the sun is at a low angle, but increases to 80 per cent as the sun goes up to a nearly normal incidence on the absorbing surfaces. While the sun angle is most favourable, about noon, there is a noticeable lag in the efficiency figure which attains its maximum value about 1½ hours later. This is brought out in Fig. 3 which shows average values for January 1954.

Most of the observations taken with the present arrangement were made with a rate of flow of water of 18-19 gallons per hour, and it will be seen from

TABLE 2. 24 December 1953. Sky clear with scattered clouds. Wind velocity 5 to 6 ft./sec. Humidity 63-56 per cent. Air temperature at noon 74° F.

Indian standard time	*Heat absorbed by water Q_w B.Th.U./ft.²/hr.*	I_t	$\eta_T = \frac{Q_w}{I_t} \times 100$	*Solar intensity normal to glass surface I, B.Th.U./hr./ft.²*	$\eta_N = \frac{Q_w}{I} \times 100$
12.30	185.5	289	62.7	263.3	70
13.00	173.1	282	61.4	273.8	63
13.30	227.0	291	78.0	272.5	83
14.00	208.1	281	74.1	249.5	83
14.30	169.7	246	69.0	203.1	83
15.00	119.6	217	55.1	163.7	73
15.30	95.7	183	52.3	144.0	66

Fig. 3 that the rate of heat absorption increases from 4,000 B.Th.U/hour at 10 a.m. to about 10,500 B.Th.U/hour at 1.30 p.m.

Since domestic water heaters are more likely to be used with a water tank, a 100 gallon water reservoir was included in the line and the performance shown in Fig. 4 is typical of this arrangement. The upper curve in this figure shows the temperature as the water leaves the upper header tube and enters the top of the 100 gallon storage tank. The high-temperature side shows, over a period of 4 days, a progressive increase in the maximum temperature recorded. During this period the water temperature rose from a maximum of 156° F. for the first day to 186° F. for the fourth day, that is, a progressive increase of some 30° F. It also shows that there is a rise of 75° F. over the previous night's lowest temperature in the system. The cooling off during the night's storage is 10-15° F. which is a satisfactory figure. The system was under test for about 6 months, from December 1953 to May 1954, and the records reproduced in the paper are typical of observations recorded.

A study of Fig. 5 will show how the system worked during a fortnight's run in September 1954. During that month there were several days when the sky was overcast and it will be seen that even on these days there was appreciable gain in temperature.

CONCLUSION

While we are continuing experiments with a few other models with minor modifications, we think that the present model can satisfactorily meet the domestic requirements of a small family, assuming that it requires a moderate supply of hot water for washing, bathing and cooking. The winter season in northern India, when the supply is mostly required, is about the best period for the utilization of solar energy.

We have avoided giving figures for cost of production of the unit, but it could be installed at a cost comparable with the price of a pressure type electric water heater. The unit will not require any looking after once it has been installed, except for a periodic cleaning of the glass surfaces. In the absorbers which are now being designed, a standard unit is being adopted. Each unit absorber will be 8 ft. in height by 3 ft. wide. These will be easier to transport and for larger family requirements three or more could be paralleled, thus greatly increasing the flexibility of the system. Also it is proposed to have two sizes of water tanks, one with a storage capacity of 50-60 gallons and the other with 100 gallons. We have found the rock wool insulation quite satisfactory and since it is manufactured locally the cost is lower than for other insulating materials.

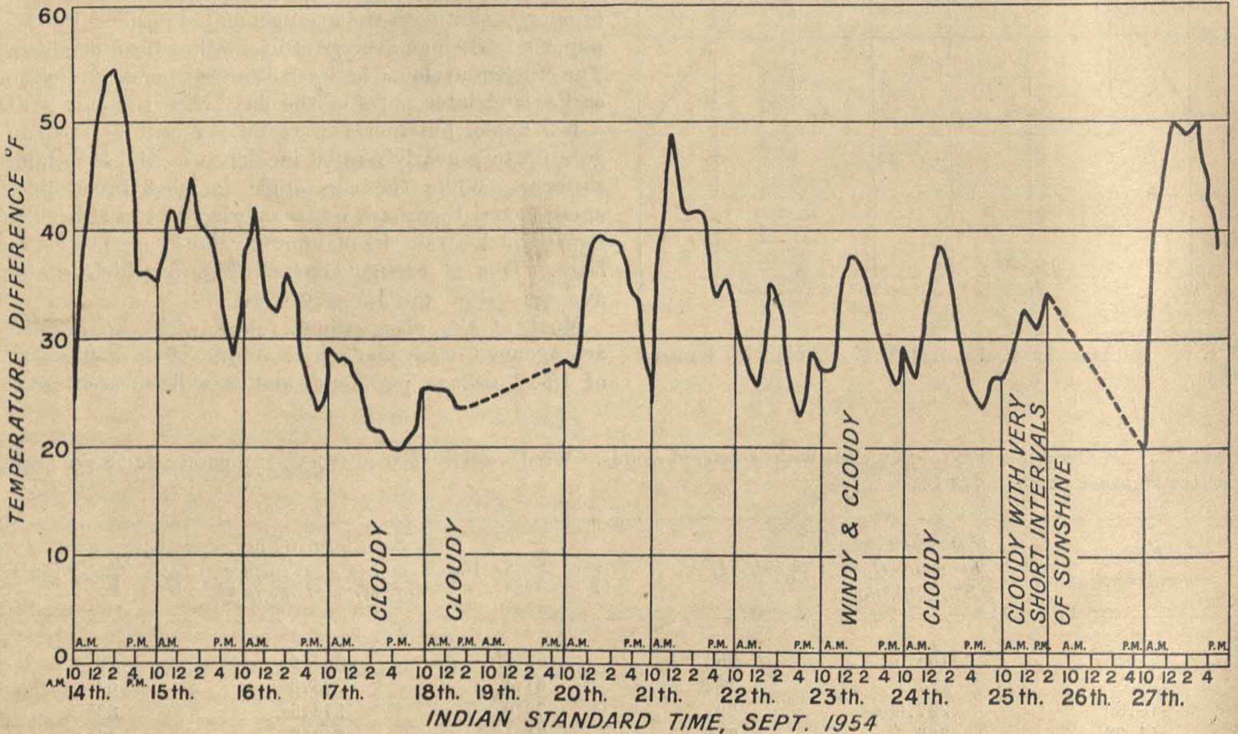

Fig. 5. Temperature differences recorded from 14 to 27 September 1954.

QUELQUES OBSERVATIONS SUR UN CHAUFFE-EAU SOLAIRE A USAGE DOMESTIQUE

par

K. N. MATHUR et M. L. KHANNA

RÉSUMÉ

Les auteurs examinent les avantages des installations utilisant l'énergie solaire avec ou sans concentrateurs. Le succès de la méthode dépend de toute façon du nombre d'heures d'insolation disponibles et comme ce facteur est très favorable en Inde pendant l'hiver, le laboratoire a décidé de mettre au point un collecteur de chaleur à plaques plates pour fournir en eau chaude une famille de quatre ou cinq personnes.

Le dispositif d'absorption est représenté schématiquement à la figure 1 et est entièrement décrit. Les tableaux montrent le rendement d'absorption et la figure 2 donne la moyenne de la chaleur absorbée par l'eau à différentes heures de la journée pendant le mois de janvier 1954.

Un ballon d'eau de 450 litres a été inclus dans le circuit et son rendement ressort de la figure 3. Le système entier a été mis à l'essai pendant six mois environ et l'on voit à la figure 4, à titre d'échantillon, les chiffres d'une quinzaine. Il en ressort que même quand le ciel était nuageux, le gain de température était appréciable.

Bien qu'il n'ait pas été calculé, on considère que le prix d'installation de cet appareillage serait comparable à celui d'un chauffe-eau électrique sous pression. Par contre, le coût du fonctionnement est nul.

ALGUNAS OBSERVACIONES SOBRE UN CALENTADOR SOLAR DE AGUA PARA USOS DOMÉSTICOS

por

K. N. MATHUR y M. L. KHANNA

RESUMEN

En este estudio se examinan las ventajas de las instalaciones con y sin concentradores para la utilización de la energía solar. El éxito de cualquier método dependerá del número de horas de insolación eficaz, y como éste es más favorable en la India durante el invierno, el Laboratorio decidió construir un hornillo a base de un colector plano para suministrar el agua caliente que necesita una pequeña familia para los usos domésticos.

En la figura 1 se muestra de manera diagramática el colector, del que se hace una descripción completa. En el texto figuran cuadros con el rendimiento de absorción de energía y la figura 2 muestra el promedio de calor absorbido por el agua a las diferentes horas del día, durante el mes de enero de 1954.

En el circuito se conectó un depósito de agua de una cabida de 460 litros, cuyo funcionamiento puede verse en la figura 3. Durante seis meses, el sistema fué

objeto de ensayos, y en la figura 4 se dan los resultados de quince días de funcionamiento. Puede observarse que incluso en días nublados hubo una apreciable ganancia de temperatura.

Aunque no se dispone de cifras, se considera que le grupo podría instalarse por un precio similar al de un calentador eléctrico a presión. Su funcionamiento no produce ningún gasto.

DISCUSSION

Mr. CHINAPPER. On page 204 of their paper the authors describe the construction of their flat plate absorber and state that more than one glass plate in front of the absorbing surface is disadvantageous for two reasons—firstly, because it would be difficult to keep clean and secondly, because it would be more expensive.

I am not quite convinced that the little extra effort required to keep the glass clean would not be fully worth while. Again, though there is a saving in expenditure in not having glass plates, one could save also by having a smaller absorber with glass plates, for such an absorber would certainly be smaller because of its greater efficiency.

In the experiments on a model flat plate absorber conducted by me under Dr. H. Heywood at Imperial College it was found that the efficiency of collection with no glass plates was 71 per cent. With one glass plate however the efficiency was 82 per cent, and the energy actually collected was 10 per cent more. With two glass plates the efficiency was about 90 per cent, and the energy collected was still a little more than with no plate. These figures of efficiency must be considered in relation to the mean temperature of the absorber—because it is the heat loss from the absorber which decides the efficiency of heat collection, and the heat loss depends upon the temperature difference between the absorber plate and the atmosphere. Dr. Heywood states that:

$$Hc = c(t - ta)^{1.3}$$

where Hc = heat loss and c = constant depending on the number of glass plates and is 0.42 for one plate, 0.30 for two plates and 0.22 for three plates.

The figures for efficiency I have quoted above were obtained for a temperature difference of about 4° F., and show that there is a decided advantage in having glass plates in front of the absorber even with such a small temperature difference.

Indeed at higher temperatures of collection, when the absorber plate is at temperatures more than 60° F above atmospheric temperature, two glass plates are necessary to collect the greatest amount of energy with the greatest efficiency of collection.

This brings me to the second point, and that relates specifically to the figures for the efficiency of collection (Table 2). It would certainly be more helpful if the atmospheric temperature together with the inlet and outlet temperatures of the water to the absorber were given as well, so that the efficiency could be seen in relation to the mean temperature of collection. For the reasons stated above, without these temperatures it is difficult—indeed almost impossible—to have a complete idea of the performance of the absorber.

Finally I would like to commend the design of the water passage in the absorber. Flow between the two layers of thin gauge sheets is an efficient and economical arrangement for heat transfer from the absorber plate to the water.

Domestic solar water heaters deserve much more popularity and use in northern India where hot water is necessary in the winter months. For this reason the efforts of the authors must be specially commended.

M. TROMBE. Je voudrais donner la précision suivante : l'emploi rationnel d'un double vitrage a été étudié par MM. Peyches et Esches Desrivières (Saint-Gobain, France). L'épaisseur des vitrages ne joue pratiquement qu'un rôle faible ; par contre la distance des deux vitrages ne doit pas être inférieure à 0,8 à 1 cm^2 ni supérieure à 10 cm pour que l'effet calorifugé soit maximum.

En pratique, d'ailleurs, pour le chauffage de l'eau plusieurs vitrages ne sont pas nécessaires.

Il a été étudié à Mont-Louis, dans les mêmes conditions, des récupérateurs solaires identiques entre eux mais comportant un ou deux écrans de verre. Le double écran donne un faible gain de température par rapport à l'écran à un seul vitrage. Il n'en serait probablement pas de même pour le chauffage de l'air si celui-ci circulait entre les écrans avant de rejoindre la surface du récepteur.

L'emploi de deux écrans est, par contre, très utile pour la climatisation des pièces, car, s'il n'améliore pas beaucoup le captage de l'énergie pendant la durée du rayonnement solaire, il atténue notablement, la nuit en particulier, les pertes de calories du système.

ARTICULATED AND SEMI-ARTICULATED LOW-COST HOT-FOCUS SOLAR ENERGY CONCENTRATORS

by

A. L. GARDNER

INTRODUCTION

During the past eighteen months the writer has devised and constructed two new types of hot-focus solar energy concentrator that, in his opinion, make possible the immediate extension of the use of solar energy from a laboratory research tool to many practical industrial and domestic fields. The object of this paper is to give, for the first time, a general technical description of these concentrators and of the principles on which they are based.

Between them, these concentrators provide a fundamentally new means of collecting solar heat in usable quantities and at useful temperatures. Previous attempts have been divided by many writers into two main classes:

1. Hot plate or glass-house type collectors, in which the trapping effect of glass over a heat-absorbing surface is used to retain the incident energy. The advantage is that large quantities of heat can be collected by a single plant, since the cost per unit area of the collecting apparatus need be no greater in a large plant than in a small one. The disadvantage that has prevented wide general industrial use is that the heat collected by this method is always at too low a temperature for most industrial purposes; the same factor severely limits its domestic utility.
2. The curved mirror on a single mounting (or an approximation to a curved surface built up of plane mirrors) can give very high temperatures if well formed and if a curvature is given in two dimensions so as to produce a "point focus" and not a line focus. The great disadvantage is that, if attempts are made to increase the size of this type of plant to provide a usable quantity of heat for industrial purposes, the plant becomes enormously costly and unwieldy. Even if expense of construction is disregarded, the practical limit of size of paraboloidal mirrors is reached when the diameter is of the order of 30 ft.

Research and development work has hitherto been confined mainly to adapting the "user" apparatus to conform to the limitations of the above types of collecting or concentrating plant; for example, to design heat engines that will work efficiently at low temperatures or with small quantities of heat, or to find new and more efficient methods of converting heat into other forms of energy. These are all long-term efforts, but may yield results in time. In effect, they accept that existing methods of collecting the sun's energy are not suited to normal economic exploitation, and to overcome this obstacle research is being devoted almost entirely to improving the efficiency of "user" apparatus to match the relatively low temperatures or the small quantities of heat provided by existing types of collecting device. The writer, appalled at the difficulties inherent in this course, decided to attack the problem at the "collecting" end, to try to invent a new type of collecting apparatus that would satisfy the industrial requirements of temperature, quantity of heat, and initial cost. The first result was the fully articulated sun power concentrator, so called because the main feature distinguishing it from previous sun concentrators is that it employs a large number of mirrors which are independently mounted but linked together for control purposes. The semi-articulated plant, evolved rather later, is quite different in principle, and is the more suitable type for plants of up to about 200 ft.^{2} of collecting surface.

THE FULLY ARTICULATED PLANT

The fully articulated plant consists of a large number of separate plane mirrors, each on a separate mounting, and normally disposed over a level site so as to reflect the sun's heat upwards towards a fixed raised focus situated to one side of the group of mirrors.

To enable the plant to "follow" the sun's motion, the mounting for each mirror is designed as a simple linkage in which one bar (the "sun bar") can be moved to make it point at the sun, and another bar (the "focus bar") is permanently fixed pointing at the focus. The mirror is carried on the upper ends of these two bars in such a way that, when the sun bar is pointed at the sun, the normal to the mirror bisects the angle between the sun and the focus, and the sun's rays are therefore reflected to the focus. The sun bars of the mirror mountings are linked together in groups of convenient size, so that a whole group of mirrors can be operated by a single control. A plant would normally consist of a number of such groups, all the groups directing the sun's heat to the same focus.

DIMENSIONS

The quantity of heat required at the focus determines the overall size of the plant, i.e. the total area of mirror surface required. For example, let us take a rough optimum value of incident radiant heat of 1 kw. per m.^{2} and an overall efficiency of collection of, say, 50 per cent; then, to obtain 100 kw. of radiant heat at the focus the total mirror surface must be 200 m.^{2}.

The temperature obtained at the focus depends on the number of mirrors used, i.e. on the "concentration ratio". Fifty mirrors reflecting the sun's heat on to an area the size of one mirror will produce a theoretical "black body" temperature of about 600° C.; 200 mirrors will give about 1,000° C. A plant of 200 m.^{2} mirror surface consisting of, say, 400 mirrors, each of an area of ½ m.^{2}, could therefore give temperatures of the order of 600-1,000° C. if the absorbing apparatus at the focus was of reasonable efficiency.

The optimum size of mirror, from the point of view of economy in construction, probably lies within the range of 1 ft. × 1 ft. for the smallest plants to about 2 ft. by 3 ft. (or possibly slightly larger) for large plants.

The height of the focus depends on the size of the plant. As a rough guide, the small plant of 49 ft.^{2} mirror surface erected by the writer at the National Physical Laboratory in New Delhi has a focus 8 ft. higher than the surface of the mirrors; in the original plant made by the writer on the roof of his flat, the corresponding values were 29 ft.^{2} and 5 ft. For any given limiting angles of reflection it is obvious that the area of mirror surface that can be used will vary roughly as the square of the height of the focus. On this basis a plant of 200 m.^{2} of mirror surface would need a focus about 40 ft. above the level of the mirrors. These considerations are based on the assumption that all the mirrors are situated within a sector of about 45° on either side of the line running due south from the focus (which is the case with both of the plants hitherto erected). It would be possible to increase the mirror surface without increasing the height of the focus if groups of mirrors were also employed in, say, the north, east and west directions from the focus. Groups of mirrors in these directions would have to be "switched out" when the direction of the sun coincided with that of the focus from any particular group, since under these conditions the linkage employed in the mirror mountings will not function; and in any case the shadow of the "user" apparatus would then fall on that group. The solid angle formed by the incident rays at the focus would also be much greater. Nevertheless, for certain types of use this method might be practicable, and preferable to increasing the height of the focus or using several separate plants.

If mirrors are used only on the "equator" side of the focus, they can extend to distances from the focus such that the angle of elevation of the focus as seen from the mirror is about 30°. The actual value of this "limiting angle" for any given plant will depend on a number of factors, such as the ratio of the value of the energy collected to the cost of installation and maintenance of the mirror system, the variation in the cost of raising the focus to various heights, the latitude of the site (as affecting the range of altitudes of the sun), etc. If mirrors, are used on the "polar" side of the focus, the latitude factor becomes less important, since no mirror on that side will receive rays at more than 45° to the normal to the mirror; with increasing distance from the focus there will, however, be increasing shadowing of one mirror by another unless the mirror spacing is increased, and the cost of this increased spacing becomes the economic factor that determines the limiting angle.

In general, the spacing between mirrors should, of course, be as small as possible without allowing any one mirror to foul an adjacent mirror. If the mirrors are unnecessarily widely spaced, the cost of construction of the mirror system and also the height of the focus is increased. On the other hand, it would be very annoying to construct a plant and then to find that certain mirrors foul one another when the sun is in certain directions. The calculation of the minimum spacing that will ensure clearance under all conditions is extremely laborious if done for a single plant, and until basic tables have been computed it is probably better to work by the following rough rules that have been derived from experience. They apply only to plants using square mirrors, with all the mirrors on the "equator" side of the focus (for which the minimum spacing is determined rather by the risk of fouling than by the amount of shadowing):

1. The "normal" spacing (between centres) is 1½ times the size of the mirror. For example with mirrors 1 ft. square, the spacing between centres of adjacent mirrors, in either direction, should be 1 ft. 4 in.
2. This "normal" spacing will not be sufficient for mirrors that are closer (in plan) to the focus than

½ h, where h is the height of the focus; and an even wider spacing is required if mirrors are employed outside a sector contained within lines running at 45° to the meridian (unless these mirrors are well away from the focus).

3. For groups of mirrors situated well away from the focus and within the above-mentioned 45° lines, the spacing between successive rows of mirrors (i.e. the spacing along the north-south line) can be reduced to 1¼ times the size of the mirror.

Construction is simplified if the spacing between mirrors is kept constant for all the mirrors in any one group, although the spacing between rows need not be the same as that between the mirrors in a row.

As mentioned above, the total area of mirror surface to be used is determined by the output required, while the size, and hence the number, of mirrors must (within the economic limits mentioned) be chosen to give the necessary concentration ratio for the focal temperature that is needed. In determining the size of mirror, allowance must be made for the fact that the actual concentration ratio at the focus will be less than that indicated by the total number of mirrors, owing to imperfections in the construction of the mirror mountings and to small errors in assembly. These errors, together with imperfections in the planeness of the mirror glass, need not cause any undue loss of concentration if a normal engineering standard of accuracy is maintained in the making and assembly of the plant. With a very large plant the distance from the further mirrors to the focus will be large, and any angular error in the direction of the reflected rays will produce a greater linear displacement of the images at the focus than the same angular error would cause in a smaller plant; but since, in view of the upper limit on the economic size of any mirror, the very large plant will be using more mirrors than are needed purely to achieve a given concentration ratio, in such a plant, this greater displacement of the images can be accepted. Roughly speaking, the size of mirror to be used in a small plant will be determined by the concentration ratio that is needed, while for larger plants it will be set by the economic limitation on the size of mirrors.

The mirrors used on the fully articulated plants so far erected by the writer have been square, but there are certain advantages in using rectangular mirrors, with the longer dimension in the direction of the focus; in particular, this would allow the pivot of the mirror to be placed nearer to the centre of the mirror without unduly reducing the dimensions of the linkage forming the mounting.

The number of mirrors in each group will be determined by the most economic and convenient size of the suspended frame for operating the sun bars. Ten or 12 ft. is probably the maximum dimension that can be given to a light frame without the risk of deflections becoming too large. Sixteen large mirrors, each 2 ft. by 3 ft. might form a convenient group in a large plant, while more mirrors could be employed in each group in a smaller plant using smaller mirrors. With mirrors 1 ft. square, it is found that 49 mirrors (7 × 7) is about the maximum number that can be used conveniently as a group, and actually 36 would be more convenient. As mentioned above, however, the semi-articulated type of plant described later in this paper is preferable for plants of less than 200 ft.^{2} of mirror surface.

TYPES OF CONTROL

Three different ways of controlling the sun bars of a group of mirrors in a fully-articulated plant may be distinguished:

Free Suspension of Control Frame

In this type the control frame is suspended on a "double parallelogram" linkage so that it can be swung freely in any direction (but not skewed), and thus enables all the sun bars of the group to be pointed at the sun. In this type of suspension no special provision is made to restrict the movement of the frame to accord with the sun's apparent path in the sky—i.e. there is no axis representing the earth's axis, no special adjustment for the sun's declination, and the plant is not necessarily aligned accurately with respect to the meridian.

"Equatorial" Suspension of Control Frame

In this type the sides of the control frame are accurately aligned with the true N.-S. and E.-W. directions. The frame is carried on, say, four suspension units, each of which consists of an axis pointing permanently to the celestial poles, about which rotates a bar hinged to the control frame; this bar can be set off north or south of the equator through angles corresponding to the sun's declination at any particular time of the year.

"Equatorial" Arrangements incorporated in each Mirror Mounting

In this type the sun bar of each individual mirror mounting is set up on an "equatorial" basis, hinging about a polar axis and capable of being set off north or south for the sun's declination. The interconnexion between the sun bars in a group of this type is very simple; plain push-pull bars between the sun bars of the mirrors in each E.-W. row is sufficient, since the sun bars are constrained individually to move only in the daily path of the sun.

The writer has constructed plants using each of the above types of sun bar control. Each has its advantages and disadvantages.

The first type (free suspension of control frame) was used in a small model having 36 aluminium reflectors each 5 in. square, constructed by the writer during the autumn of 1953 when work on the larger plant of 29 ft.^{2} was held up by the monsoon rains. The model, now dismantled, showed that the method can be applied without difficulty. Its advantage is simplicity of construction; its disadvantage is that the drive to the frame must control it in two dimensions (the problem is that met with in astronomical observatories when using an alt-azimuth instrument to "follow" a heavenly body).

The second type, with the control frame suspended equatorially, is employed in the 49 ft.^{2} plant erected by the writer at the National Physical Laboratory of India with the aid of workshop facilities kindly afforded by the director of the laboratory. This suspension requires only a uniform angular drive of 15° an hour to ensure that all the sun bars are kept directed at the sun. The sun's declination must be set on each of the four suspension units, and adjusted every few days. The construction of the frame and suspension units must be sufficiently rigid to avoid undue amounts of deflection or skew distortion.

The third type, in which every sun bar individually is mounted equatorially, was used by the writer in building the "original" plant of 30 ft.^{2} area on the roof of his flat in New Delhi. This type was chosen mainly because the very limited "workshop" facilities afforded by a dining room chair and a set of carpenter's hand tools made the construction of a large but stable control frame a matter of uncertainty, whereas the third type control, with restraint at every mirror mounting, is inherently stable. The obvious disadvantage of this type is that changes in the sun's declination have to be set on every sun bar individually.

TYPES OF MIRROR MOUNTING

The essential parts of a mirror mounting for a fully-articulated sun power plant are: (a) a member permanently directed at the fixed focus and capable of rotation about the axis that points at the focus. This member is referred to as the "focus bar"; (b) a member that can be directed to point at the sun, referred to as the "sun bar"; (c) a carrier for the mirror, hinged to the upper end of the focus bar by a hinge at right angles to the axis of rotation of the latter and engaged by the upper end of the sun bar through a slide parallel to the surface of the mirror and at right angles to the hinge of the mirror carrier.

The dimensions and alignment of the above components must be such that an isosceles triangle is formed by the focus bar, the sun bar and the slide, the sides of this triangle constituted by the first two of these members being of equal length while the side formed by the slide is variable.

Many designs of mirror mounting to meet the above requirements could, of course, be evolved. The writer has tried out a number of different types, the most successful of which appears to be one in which the lower end of the sun bar is prolonged to carry the control frame, the weight of which is thus more or less counterbalanced by the weight of the mirrors.

THE SEMI-ARTICULATED PLANT

The semi-articulated plant resembles the fully articulated plant to the extent that it employs a number of flat mirrors arranged on a horizontal plane and reflecting to a fixed focus. Here the similarity ends, for the method of mounting and of directing the mirrors so as to allow for the sun's motion is quite different.

In its simplest form, the semi-articulated plant (see plate V a) consists of a horizontal rectangular frame lying on the ground and spanned by a number of bars capable of being rotated about their (longer) horizontal axis. Changes in the bearing of the sun are allowed for by revolving the whole frame in the horizontal plane about a point immediately beneath a selected fixed raised focus, so as to keep the rotatable bars at right angles to the bearing of the sun. A row of plane mirrors (of any convenient shape) is fixed permanently along the upper surface of each bar, the mirrors having an "inward" tilt that increases progressively with the distance of the mirror from the middle of the bar. The angle through which the mirrors are tilted is such that, for a selected mean altitude of the sun, the reflected rays from the mirrors can be made to converge to the above-mentioned fixed focus when the bars carrying the mirrors are rotated to allow for the sun's altitude.

For any altitude of the sun other than that selected for determining the permanent inward tilt of the mirrors, the degree of convergence in this transverse direction is only approximately correct. In practice, however, it is possible to choose a position for the focus such that the error in convergence lies within acceptable limits for any useful altitude of the sun.

A second approximation is involved in this type of plant, in that, strictly speaking, the mirrors on any given bar cannot all be made to converge correctly to the focus, even for altitude, except when the altitude of the focus as viewed from the middle of the bar coincides with that of the sun. But this error, again, can be made to remain within acceptable limits by suitable design of the plant.

From an engineering point of view it appears probable that this type of plant is suited to sizes up to about 200 ft.^{2} of mirror surface, beyond which it would become cumbersome and should be replaced by a fully articulated plant.

A semi-articulated plant designed by the writer is now (August, 1954) approaching completion at the National Physical Laboratory of India (see plate V b). This plant has a total mirror surface of 192 ft.^{2}, and has therefore a heat-gathering power approximately equal, at the higher altitudes of the sun, to that of a paraboloidal reflector of 13-14 ft. diameter. The mirrors are each 1 foot square, so that the theoretically attainable concentration ratio for this plant is 192 to 1. The horizontal frame is about 16 ft.², and is turned by hand about the fixed focus stand, travelling on twelve 4 in. diameter rubber-tyred wheels that run on three concentric circular concrete tracks. The rotating bars carrying the mirrors are arranged in three "banks", the bars in each bank being linked to a common control handle.

In smaller versions of the semi-articulated plant, with which the writer has been carrying out experiments at home, the wheels are dispensed with and the frame is simply dragged round the focus stand into alignment with the sun. Similarly, the control of the rotating bars in these smaller plants is effected simply by turning each bar individually by hand so as to bring the sun's rays into the focus.

Fuller details of these semi-articulated plants will be given in a later paper. Meanwhile, this type of plant shows promise of providing a simple, cheap and robust form of concentrator for many domestic and small industrial uses.

FUTURE DEVELOPMENT

The writer is of the opinion that the new types of solar energy concentrators described above are capable of immediate practical application to many industrial and domestic uses where the energy is required in the form of heat. For application for these purposes the need is not for research but for development and manufacture—i.e. for the services of design engineers, field surveys of needs, field trials of prototypes, and manufacturing facilities and funds. For other uses, particularly for those involving conversion of the heat into power, research on the most effective means of conversion is, of course, desirable, although it is probable that the concentrators could give economic results even with existing types of appliance adapted to operate with radiant heat.

The writer also considers that greater priority should be given to getting these plants into widespread use for purposes for which they are immediately suitable (e.g. for small-scale manufacturing processes involving the use of heat) than to other applications that, although they may represent more pressing national needs, would involve considerable amount of research on the form of the user appliance. The widespread use of solar energy concentrators for the simpler applications would immensely facilitate and encourage the solution of problems involved in extending their use to other purposes.

The smaller forms of the semi-articulated plant are so simple that they could readily be constructed by village craftsmen. For the larger plants, series production in a factory would be desirable, and the writer has therefore covered both types of plant (fully articulated and semi-articulated) by patents. He will, however, be glad to give every facility or help that is within his power to institutions wishing to construct plants for research or experimental purposes, and to organizations or individuals who wish to make field trials of plants of these types.

L'UTILISATION DE L'ÉNERGIE SOLAIRE

par

A. L. Gardner

RÉSUMÉ

L'auteur décrit deux types nouveaux de concentrateurs d'énergie solaire à foyer ardent qu'il a mis au point lui-même. On peut classer les dispositifs antérieurs en deux groupes principaux : 1° les collecteurs du type serres chaudes, capables de recueillir de grandes quantités de chaleur à base d'hydrogène, mais dont l'utilisation pratique industrielle est limitée du fait de la basse température obtenue ; et 2° le miroir-courbe à monture unique qui réalise de hautes températures, mais ne fournit des quantités suffisantes de chaleur que contre un grand prix d'installation. Comme l'appareillage qui utilise la chaleur du collecteur est déjà l'objet

de recherches et de travaux de perfectionnement, l'auteur a pensé qu'il était plus avantageux de construire un groupe de collecteurs nouveaux. Le premier modèle, qui est un concentrateur entièrement articulé, comporte un grand nombre de miroirs à montage séparé, mais reliés par un système de contrôles communs. Les miroirs sont disposés sur une aire plate de façon à refléter la chaleur du soleil de bas en haut sur un foyer fixe surélevé situé sur un côté du groupe de miroirs. Les miroirs sont reliés de façon à pouvoir suivre le mouvement du soleil sans cesser de refléter la chaleur sur le foyer fixe. La quantité de chaleur recueillie au foyer dépend de la surface totale des miroirs, tandis que la température dépend du nombre de ces derniers. La hauteur du foyer dépend de la taille de l'installation puisque pour un angle de réflexion donné, la surface du miroir utilisable variera en gros comme le carré de la hauteur du foyer. En général, le miroir sera du côté équateur du foyer, mais dans certaines conditions on pourra également situer les miroirs à l'est et à l'ouest de ce dernier. Il existe des règles approximatives permettant d'espacer les miroirs, selon les données de l'expérience, de façon qu'ils n'interfèrent pas l'un avec l'autre, encore qu'il soit en principe possible de calculer l'espacement minimum assurant un libre jeu dans toutes les conditions. Un soin particulier doit être apporté au calcul de la dimension et de la forme des miroirs ainsi qu'à leur disposition par groupes à commande unique. L'auteur expose trois types de commandes. Le cadre de commande étant librement suspendu peut être facilement orienté dans toutes les directions : c'est un dispositif de construction simple, mais le réglage doit pouvoir se faire dans deux plans. Avec la suspension équatoriale, les côtés du cadre de commande sont exactement alignés sur le nord géographique et orientés sud, est et ouest. Cela n'exige qu'un entraînement uniforme de 15° par heure pour assurer un positionnement correct de tous les miroirs. La troisième méthode prévoit un dispositif équatorial incorporé à chacun des miroirs. En conclusion de cette section l'auteur a cité plusieurs types de montages de miroirs.

L'installation semi-articulée est basée sur le même principe, mais le mode de montage et d'orientation des miroirs est différent. Elle consiste essentiellement en un cadre horizontal rectangulaire posé sur le sol et portant à intervalles un certain nombre de barreaux capables de tourner le long de leur axe longitudinal (horizontal). Pour compenser le déplacement du soleil, on fait tourner le cadre entier dans le plan horizontal sur un point situé au-dessous et à l'aplomb d'un foyer fixe surélevé, de façon que les barreaux restent à la perpendiculaire du soleil. Une rangée de miroirs plans de forme adéquate est fixée à demeure à la surface supérieure de chaque barreau. Les miroirs sont inclinés vers l'intérieur et d'autant plus qu'on s'éloigne du centre du barreau. L'auteur étudie les approximations qu'emploie cette méthode et donne quelques exemples.

Il considère que ces nouveaux types de concentrateurs d'énergie solaire, à condition qu'ils bénéficient d'une mise au point suffisante, devraient pouvoir être rapidement utiles pour nombre d'utilisations industrielles et ménagères qui exigent de l'énergie sous forme de chaleur.

LA UTILIZACÍON DE LA ENERGÍA SOLAR

por

A. L. GARDNER

RESUMEN

El autor describe dos nuevos modelos de hornos solares que ha inventado y construído él mismo. Los dispositivos anteriormente concebidos pueden clasificarse en dos categorías: 1.ª los colectores de placa caliente o de tipo de invernadero, que pueden captar grandes cantidades de calor por un precio módico pero cuyo empleo no es posible generalizar, sobre todo en la industria, ya que no permiten obtener temperaturas elevadas; 2.ª los hornos, que consisten en un espejo curvo instalado sobre una montura única, que permiten obtener temperaturas elevadas, pero cuyo precio de costo es alto cuando son bastante grandes para producir cantidades

de calor suficientes. Aunque muchos investigadores e ingenieros ya han tratado de adaptar los aparatos que utilizan el calor de los colectores a las características de esos dos tipos, el autor ha estimado preferible construir un nuevo modelo de colector. El primer aparato por él imaginado, el horno solar integralmente articulado, se compone de un gran número de espejos montados cada uno de ellos en una montura diferente, pero conectados a un mando único. Están dispuestos en un emplazamiento plano a fin de reflejar el calor solar hacia arriba en dirección a un foco fijo situado a un lado del grupo de espejos. Estos están montados de modo que puedan seguir el movimiento del sol y reflejar constantemente el calor hacia el foco fijo. La cantidad de calor que es posible obtener en el foco depende del área de la superficie reflectora, mientras que la temperatura depende del número de espejos. La altura del foco depende de la dimensión de la instalación, ya que para un determinado ángulo límite de reflexión, el área de la superficie reflectora que puede utilizarse varía más o menos de acuerdo al cuadrado de la altura del foco. En general, los espejos están colocados del lado ecuatorial del foco, pero en determinadas condiciones, se pueden utilizar también espejos colocados al este y al oeste. Las reglas aproximadas que deben seguirse para que dos espejos vecinos no entren en contacto entre sí han sido conseguidas empíricamente, aunque en teoría sea posible calcular el espaciamento mínimo que permite a cada espejo girar libremente en todas las condiciones de uso. La determinación de las dimensiones y de la forma de los espejos así como su montaje en grupos, cada uno de los cuales obedece a un mando único, deben ser objeto de especial atención. El autor describe tres sistemas de mando. La suspensión libre del cuadro de mando permite desplazarlo a voluntad en todos los sentidos; ese dispositivo es de fácil construcción, pero la transmisión conectada con el cuadro debe funcionar en dos planos perpendiculares. Con el sistema de la suspensión "ecuatorial" del cuadro de mando, los lados del cuadro están exactamente orientados de norte a sur y de este a oeste (direcciones verdaderas). Una suspensión de ese tipo sólo exige un desplazamiento angular uniforme de 15° por hora para mantener todos los espejos dirigidos hacia el sol. Por último, el tercer sistema se basa en el empleo de dispositivos "ecuatoriales" incorporados en el soporte de cada espejo. La sección consagrada a los hornos íntegramente articulados termina con una descripción de algunos tipos de soportes de espejos.

La instalación semiarticulada se funda en el mismo principio que la instalación íntegramente articulada, pero el método de montaje y de orientación de los espejos es distinto. El aparato comprende un chasis rectangular horizontal que descansa sobre el suelo, provisto de cierto número de vástagos dispuestos en forma de peldaños de una escalera, que pueden girar alrededor de su eje longitudinal. Para seguir al sol en su trayectoria, se hace girar todo el chasis sobre el plano horizontal alrededor de un punto situado perpendicularmente al foco, de manera que el eje de las barras esté en todo momento en ángulo recto respecto a la dirección del sol. Cada barra lleva una fila de espejos planos, de forma apropiada, cada uno de los cuales está inclinado hacia el medio de la barra según un ángulo que aumenta a medida que se acerca al borde del chasis. El autor examina, luego, las aproximaciones que entraña ese método y cita algunos ejemplos.

Concluye diciendo que esos nuevos modelos de hornos solares podrían, después de haber sido objeto de una preparación técnica conveniente, ser utilizados inmediatamente para numerosos usos industriales y domésticos que exigen energía calórica.

DISCUSSION

M. Trombe : Je suis heureux de féliciter M. Gardner pour sa belle réalisation qui sera, certainement, utilisée en particulier pour la cuisine solaire. Dans ce cas, l'abaissement du prix de revient étant le facteur impératif, il ne peut être question de proposer une modification, si peu coûteuse soit-elle, qui augmente ce prix.

En ce qui concerne la production de vapeur, on pourrait peut-être améliorer les conditions de travail en mettant chacune des glaces sous contrainte mécanique (poussée avant et arrière), ce qui a pour effet de diminuer beaucoup la surface d'éclairement et par conséquent d'augmenter la densité d'énergie.

Une telle disposition, qui a donné de bons résultats à Mont-Louis, est particulièrement utile lorsque le verre support de la couche d'argent réflectrice est du verre à vitre qui donne des grandes aberrations.

POWER FROM LEAVES

by

N. W. PIRIE

There are a few sources of energy that do not depend on past or present sunlight. Examples are the atomic nucleus, the tides, and the internal heat of the earth; these have not yet been used on a significant scale and their exploitation will raise a number of serious difficulties; but we are not concerned with them at this symposium. Our main source of energy is coal and this depends on past sunlight. It is a wasting asset, because conditions no longer lead to the formation of coal and similar fuels at a rate in any way comparable to the rate at which we burn them; a time must come when the workable supplies will be exhausted. The first consequence to consider is the failure of that power source; other consequences will be considered later.

Once our capital of coal, oil and peat is exhausted, solar energy must come from current radiation. Three main ways of getting it are generally considered: water power, wind, and the differences in temperature of different layers in the sea and other large bodies of water. There have also been suggestions that banks of thermo-couples could be used to make electricity in isolated situations. Others will be dealing with these methods. They have in common the defect that, essentially, they use radiation wastefully as a source of heat, and this is also a defect of all the methods in which mirrors or lenses are used to concentrate the radiation and so raise steam or in some similar way drive an engine. If light could be used directly a more efficient system would be possible; considerable effort is now being put into the design of photocells that are efficient in full sunlight. It may be that these will be successful, so that by exposing photosensitive surfaces to sunlight we shall get an electric current corresponding to say 1 per cent of the energy content of the light. That part of my argument which relates to energy production would then probably become largely irrelevant; certainly so, if 10 per cent efficiency could be achieved [1].[1] But because this may not prove possible, and also because other factors are involved, the argument will be developed.

In the processes considered so far, either radiation sets matter into motion, so that we can use its kinetic or potential energy, or it establishes an electric potential difference. Photosynthesis establishes a chemical potential, the usefulness of which depends on the environment in which it takes place. Thus coal is only of value as an energy source because it exists in an environment which includes an atmosphere containing oxygen. The essential feature of photosynthesis, both when the coal measures were laid down and now, is the dismutation of carbon dioxide into highly oxidised substances which we can recombine at our convenience. Secondary changes lead to the formation of carbon, as in the formation of coal, but the most common first stable stage is the formation of a carbo-hydrate and oxygen. This is the main process that the green plants carry out, but it is far from being the only possibility. Even biological photosynthesis is not restricted to it. Thus, in a photoreceptor such as the eye, light establishes a chemical disequilibrium that supplies the energy to start a nerve impulse.

The scope of non-biological photosynthesis is very much wider, and nothing is gained by thinking of it narrowly as leading exclusively to a reduced carbon compound and oxygen; the formation of an oxidised compound in a reducing environment would be as effective. Any local chemical disequilibrium established by light would, in principle, be useful as a source of power, and the chlorophyll-based system which produces mainly carbo-hydrate offers no special advantage in theory. It does, however, already exist on a large scale. For this practical reason, and also because the system can be used to produce food at the same time that it produces power [9], this paper will be limited to the chlorophyll system and to the steps that could be taken to industrialize it.

Estimates of the total quantity of carbon fixed by photosynthesis vary, but 40 G tons[2] a year is a reason-

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1. The figures in brackets refer to the bibliography on page 224.
2. G = giga or abaj or 10^9.

able figure and of this 16 G tons is fixed on land [11]. This is nearly 20 times more than the coal and oil used but it is much less important industrially, partly because carbo-hydrates are not such convenient fuels and partly because it is not produced in quantity at defined places but spread uniformly over much of the land and water area of the earth. If the distribution were quite uniform it would amount to 8 mg. of carbon per cm.^{2}. Large as the amount of photosynthesis is, it is only a fraction of what is in theory possible. If sunlight with an intensity of 0.36 kw./m.^{2} (i.e. about a quarter of the maximum recorded) were used—with 100 per cent efficiency for six hours a day during a 200 day year—to make carbo-hydrate, the return would be 9 g. of carbo-hydrate, that is 3.6 g. of carbon per cm.^{2}. Using these approximations and arbitrary values, natural photosynthesis appears to be a process working with 0.22 efficiency. The actual value is not likely to differ by more than a factor of 3 and we must therefore examine the reasons for the low efficiency.

Much of the energy of sunlight comes in wavelengths that green plants cannot use, and so far as can be foreseen, it could only be used by some entirely different type of photosynthesis. Much of the land surface is normally too dry or too cold for photosynthesis. Active steps are being taken to remove both limitations. Nothing more need be said about irrigation here; activity is widespread and it is something of which everyone can be justly proud. Less has been done to get rid of cold. In many areas the spring thaw is delayed because snow is white and the sunlight is reflected rather than being absorbed and thus melting the snow. There is much scope here for a study of different types of "dirt" that could be scattered over the snow surface to pick up light and hasten melting. If this were done intensively the growing season could be lengthened by several weeks. An important, though less extensive, method of diminishing the effect of low winter temperatures in temperate regions is the use for soil heating of the condenser water from electric generating stations. It is often stated that even up-to-date generating stations are only 25 per cent efficient. This means that for every 100 kwh. released by burning coal, or for that matter by nuclear fission, only 25 reappear as electricity. A few are needed to maintain draught, stoke the furnaces and so on, but most of the 75 kwh. comes out as hot water into a river or hot water vapour in a cooling tower and we throw it away. We are inefficient—not the process. Sometimes that hot water is used domestically. When this is inconvenient it could be used in temperate regions to warm the soil and maintain growing conditions during a longer period of the year.

Most photosynthesis is marine; it is sometimes limited by low temperatures but almost always limited by shortage of nutrients. Thus, in the sea around Britain, by the end of spring, phosphate has nearly disappeared from the water and all later marine photosynthesis depends on the dissolution of some already formed material. There is no immediate prospect of using marine photosynthesis as a main source of power and it is even an inadequately used source of food.

That part of the land area of the world that is normally warm enough and wet enough for the growth of plants is now the site of the most useful photosynthesis and is likely to continue to be. The return from different types of treatment is very varied and there is no reason to think that it ever approaches the maximum attainable. The literature of the subject is large and measurements have been made and expressed in so many different ways that they often cannot be rigidly compared. Some of them are actual measurements of the production on a large area in a year. A few of these are collected in Table 1.

TABLE 1.

Crop	*Where grown*	*Dry matter yield in tons per acre*	*Bibliographical Reference*
Sugar cane		40	5
Sugar cane		15	6
Elephant grass	West Australia	18	4
Eucalyptus	India	9.4	6
Palm, oil and wastes	S.E. Asia	6.8	2
Grass, sugar beet, wheat	Britain	5	12, 14
Coniferous trees	Britain	4.8	7
Swamps	Britain	4	7

As would be expected, the yields are greatest in tropical areas, mainly because of the short period of adequate temperature in the temperate zone. The rate of assimilation by different crops varies from month to month in different latitudes [14]. The maximum rates attained are not so variable as their duration, and if the rate for the best week at Rothamsted could be maintained for six months, the dry matter yield of wheat per acre would be 14 tons and that of sugar beet 24 tons instead of the 4 or 5 tons that is our present maximum. During warm weather high yields have also been recorded for some water weeds; the water hyacinth gives 4-6 tons of dry matter per acre per month [3]. If that could be maintained throughout the year it would be a record.

Extrapolations like these are not of practical importance because there is no prospect of altering the seasonal change in conditions over wide areas, but they illustrate the potentialities of crop plants during the periods of optimal conditions for them. These extrapolated figures are, therefore, the ones that should be used when the efficiencies of other photosynthetic systems, e.g. *Chlorella*, are being compared with those of crops, for the experiments on these other systems have been short, with conditions carefully and expensively maintained near the optimum.

Short term experiments with the higher plants have given similar results. For example, 3.3 m.^{2} of lucerne absorbed 36 g. of CO_2 during 80 minutes of sunshine in Iowa (U.S.A.) [13].

Had that rate been maintained for 200 days of six hours each the dry matter yield would have been more than 20 tons per acre. For two very obvious reasons experiments of this type cannot be directly compared with those in which the harvested crop is weighed: they include all the material that goes to make up roots etc. which are not harvested, or are harvested incompletely; and they do not allow for the CO_2 that is lost by respiration during periods of darkness. These are not only inevitable when sunlight is used in the middle latitudes but they are also essential for the well-being of many plant species.

From the figures in Table 1 it is apparent that a yield of 10 tons of dry matter per acre per year is good in most regions of the world, and that it is likely to be difficult to maintain 20 tons over any large area. Ten tons per acre is 0.25 g. per cm.^{2}. If the material that is being made is carbo-hydrate containing 40 per cent of carbon a good yield is therefore 11 times what we took as the world average, and if it were got under the arbitrary conditions of illumination already used, sunlight would have been used with 2.4 per cent efficiency. That would be satisfactory in the regions where it could be maintained, but they make up only a small part of the world's land area. On the other areas the problem of intensive photosynthesis is more difficult.

In areas of abundant sunshine, yields are generally limited by water shortage. Even with irrigation it is difficult to distribute water evenly, so that plants get all they can use without some being waterlogged, while there are often conflicting demands on the available water. I have argued elsewhere [9] that in many circumstances more power could be produced by growing crops with water than by using it in hydro-electric schemes. There are also many otherwise valuable areas out of reach of adequate irrigation. Plants which could photosynthesize actively with a water supply less lavish than that usually needed would be of great value, and it may be worth while considering some of the factors that lead most plants to consume so much water. The total amount that passes through even an annual may be more than a thousand times the water content of the full grown plant.

This is not the place for a thorough discussion of the survival value of the transpiration stream but it is probably safe to assume that it plays a part, not only in the translocation of materials inside the plant, but also in the uptake of nutrients from the soil. In most of the regions in which plants grow there is a shortage of some, if not all, of the main nutrients and trace elements. Consequently the plant can only get the amount it needs by combing through a very large volume of soil; it is able to do this, partly by having an extensive root system, and partly by maintaining a flow of soil water—and so of that small proportion of the nutrients that is in solution—into the neighbourhood of its roots. Under these circumstances, so far from being a disadvantage, an active transpiration stream, with evaporation from the leaves, is necessary to get rid of the water. In this way the slow diffusion of ions or molecules through the soil does not impose such limitations on the extraction of the rarer elements from it. If this interpretation of at least part of the survival value of the transpiration stream is correct, a plant that was more economical with water would have no advantage over normal plants. The ability to use water economically would, under "natural" conditions, increase the duration but diminish the intensity of the plant's metabolic activities. The question whether this would confer an evolutionary advantage, for example by increasing seed dispersal, is quantitative and there are at present no adequate observations for answering it. Dicta such as "Transpiration is a necessary evil" do not contribute to the discussion; that it is necessary seems clear, but there is no evidence that it is an evil.

In the special circumstances of an environment made and controlled by man the position is different. Here a suitable level of the essential nutrients can be maintained in the soil, so that there is an adequate amount in the proximity of the roots ready for selective absorption. One of the theoretical advantages of passing a large volume of water through from the roots to the leaves would thus be removed. A systematic attempt to select plants that would grow on well fertilized soil with a restricted water supply might be profitable, though a leaf structure that combines conservation of water with penetration by CO_2 may be difficult to achieve. What is known about transpiration gives us no reason to think that such plants would necessarily be less efficient as photosynthesizers even if their water consumption were cut down to a quarter or less. Plants selected in this way would probably not compete well with existing plants in a "natural" environment uncontrolled by man. But in that they would resemble most of the other domesticated strains of plants and animals.

There are several different ways in which this problem could be approached. We could take the existing crop plants and look for varieties unusually economical with water; we could study those plants that normally grow where there is a restricted water supply; or we could accept a desert as an area where plants not only grow slowly but grow sparsely as well. The first course is an extension of what primitive man has been doing for some thousands of years, and the more hopeful lines have already been explored. The second approach is more novel because little effort has so far been put into breeding plants that are neither immediately useful nor decorative. It is only with present day technology that we have reached the stage of looking on every plant as potentially useful; we do not necessarily mind what the plant produces so long as it produces enough of it. When the object is power production the question is no longer "How do we increase the yield of a certain commodity?" but rather "How do we use this plant which will grow vigorously in a hitherto unused environment?". The third approach calls for a rather different type of breeding programme, which can only be effective when more work has been done on the physiological mechanisms that have had survival value because they limit competition between plants for a meagre water supply. Faculties that may be of great advantage in the wild state can be detrimental when we are trying to grow a plant as a crop.

Plant breeding programmes of this type, if successful, would extend the area of intensive photosynthesis into regions of lower rainfall. There are other ways of doing the same thing. An obvious one is to allow transpiration to proceed normally without allowing the water vapour to be dissipated in the general atmosphere. This would involve the construction of a system of greenhouses over a wide area; the same roof that retains the water vapour would also retain CO_2, if that were being artificially supplemented. Such a system would work particularly well in places with low night temperatures, as condensation on the roof and a system of gutters would then maintain the circulation of water back to the roots. The roof would have to be lofty enough to hold the transpired water vapour and prevent excessive heating. It would be a formidable undertaking to build these roofs over any extensive area but the possibilities of sustaining, by slight positive pressure inside, a large transparent plastic bubble, hold out hope that it might be practicable now although it was not a few years ago.

This illustrates a general point often overlooked in discussing the technological use of biological materials; the domain of technological change should not be thought of narrowly. Thus every phase of the work from the preparation of the soil to the processing of the crop is likely ultimately to be modified, and when we find operations being carried out today by methods similar to those used in antiquity it is probable that this is because these have not yet been fully thought about rather than that they are already being done by the best methods. The industrialization of farming is only just beginning, and no argument is valid if it involves a comparison of the results of primitive farming with those of sophisticated industry.

A more extreme proposal for conserving water is to use wholly submerged plants. This also involves putting a transparent cover over the whole area and if the larger water plants were used there would be no obvious advantage, because they are as difficult to harvest as land plants and there is no evidence that they are generally more productive. By using small free floating plants, such as *Chlorella*, this difficulty is overcome. Harvesting can then be carried out with a pump and a centrifuge or filter. This system is now being intensively studied in many parts of the world and it should soon be possible to decide whether it is practicable and offers any advantage over normal farming (if that were capitalized to the same extent) and over the growth of normal plants in greenhouses. When the object of using an organism like *Chlorella* is the conservation of water it is essential that the whole system should be covered because, under most circumstances, the evaporation from an open tank is similar to that from a transpiring crop. The merit of the unicellular plants is not that they themselves conserve water but rather that they can be grown under conditions in which water can be more easily conserved. Much of the technological work done on *Chlorella* seems to be misconceived and to have been undertaken because of a failure to realize that the prominent place that *Chlorella* fills in academic literature on photosynthesis is a consequence of its convenience as a research material and not of any unusually high photosynthetic efficiency. The work would have been much more useful had it dealt with marine algae or, better still, with the nitrogen-fixing algae; we should then be able to use sea water, of which there is an ample supply, and avoid the expensive processes of nitrogen fixation.

The yield of *Chlorella* has been estimated at 15-50 tons per acre per year, depending on the amount of effort that is put into the enrichment of the culture medium with nutrients including CO_2, and on the care with which it is kept mixed [5]. This is certainly better than the yield from any normal agricultural practice but no one has yet studied the potentialities of the higher plants if all their requirements were optimally satisfied. Thus the yield of sugar cane may be as high as 40 tons of dry matter per acre, even although, towards the end of the growing period, like most tropical crops it is probably nitrogen-deficient since denitrification removes from the soil whatever nitrogen has been put in initially. Furthermore, as already pointed out, short experiments with *Chlorella* under ideal weather conditions must be compared with the short period of peak production by normal crops. A further source of inefficiency in most plants is their inability to use strong continuous light effectively. With *Chlorella* this can be circumvented by keeping the suspension well stirred so that each cell is alternately at the surface and in the shaded depths. A similar, but small, effect is produced when the leaves of higher plants flutter in the wind; and a larger effect when the compass plants turn their leaves edge on to the light. The ideal arrangement for using strong light efficiently would be a tall conical heliotropic plant with leaves set parallel to the surface of the cone so that light did not fall perpendicularly on them. The attainment of such an ideal will set the plant breeders a considerable task.

High yields of *Chlorella* are generally obtained in systems to which extra CO_2 is added. This addition increases the expense but it is considered worth while because at the low concentrations normally present in the atmosphere the rate of photosynthesis is limited by the CO_2; so also is the rate with higher plants. In any attempt at intensive growth, especially if in an enclosed space so as to conserve either heat or water, it would be well worth while to increase the CO_2 concentration round the leaves.

The developments discussed here are not likely to be undertaken yet awhile, and then the stimulus will in part be the depletion of the world's coal and oil reserves. This depletion will not leave the situation in other ways unaltered. There is about 1 kg. of reduced carbon per cm.^{2} of the earth's surface—mainly of biological origin and most of it in the shales and probably not of use as a fuel. The workable coal amounts to about 1 g. per cm.^{2} and when burnt it will add 3.67 g. of CO_2 to each cm.^{2} of the earth's surface, that is nine times the present amount. Such a state of affairs would not of course last. The sea, which already contains about 20 g. of CO_2 for each cm.^{2}, would probably take up most of this extra amount and become a little more acid in the process, unless the precipitation of $CaCO_3$ were able to keep pace with CO_2 production. With more atmospheric CO_2 an equilibrium would be established; there is some evidence that the increase is already taking place but it is hardly outside experimental error [10]. The circulating CO_2 of the atmosphere is, in effect, a catalyst and its equilibrium level is one of the factors that defines the world-wide rate of photosynthesis. A doubling or trebling of the atmospheric CO_2, which would probably also cause a rise in air temperature, would significantly stimulate plant growth—though it might well cause physiological changes and so upset mechanisms such as normal seed development in the present-day domesticated plants. It would, therefore, favour any project for using plant leaves and stalks on a larger scale; it would also increase the rate of formation of peat. If estimates of the amount of extractable coal should be much too low, or if a method were found for using the carbon in shales, then the increase in atmospheric CO_2 and the associated diminution in O_2 would be much larger, and the effects would be both catastrophic and unpredictable. If even 5 per cent of the 1 kg. of reduced carbon were mobilized and burnt, more than half the oxygen of the atmosphere would be replaced by carbon dioxide. Geochemical operations on this scale are not likely just yet, but the probable consequences stress the need for handling our carbon reserves warily.

To summarize the argument so far; in many parts of the world plants already produce 10 tons of dry organic matter per acre per year; if carefully tended they will produce 2-4 times that. The areas in which high yields are possible could be greatly extended; there is scope for technological improvement in many aspects of the growth of plants; and some of the changes brought about by the depletion of coal reserves are likely in any event to improve plant growth. Supposing that developments along these lines are in fact feasible, the next question is: How would the material that is being grown be used?

The figure 10 tons of dry matter per acre per year can be misleading because what is harvested is not dry matter but a wet crop, and the more actively it is photosynthesizing the wetter it is likely to be. The traditional way of using a crop as a source of power is to leave it to become mature and partly dry and then burn it. This method has two defects; it is slow, and it uses the land for drying instead of photosynthesis. When maximum photosynthesis is being sought in an area, that area must be kept green all the time, which means harvesting the crop when it contains only 5 to 25 per cent dry matter. Material that is predominantly carbo-hydrate will burn even when it contains as little as 20 per cent dry matter, but it is not then an effective source of power because too large a proportion of the energy is used in evaporating the water. The practicability of any power project depending on photosynthesis in plants depends also on the economy with which water can be separated from the combustible material. When the crop is dried in the field, latent heat of vaporization is supplied by radiation and from the ambient air. The heat can also be got economically by using some form of heat pump and cooling a neighbouring heat source such as a river. It is preferable to operate a system in which liquid rather than vapour water is discharged and for this a vapour compression evaporator is used; the need to supply latent heat is thus avoided, but the equipment is elaborate. There is, however, no need to pass the water through a vapour phase at all because it is only in very young material that a serious proportion of the combustible material in a crop is water soluble. It is, therefore, only necessary to press out the water; evaporating it is an extravagance.

Much effort has been expended on pressing water out of green material, but most of it has been misdirected because of an unawareness of the physiology of leaves and stems. For as long as the cells in a tissue retain their osmotic control it is very difficult to press fluid out of the tissue, though it can be pressed out as soon as osmotic control is destroyed. This is easily done by mechanical damage, by poisons, by heat, or by keeping the tissue long enough for the cells to die. Attempts to press out water have been successful hitherto mainly because of the inadvertent use of the first and last of these agents. When fuel is all that is wanted they are not the most economical agents though the rubbing or grinding of leaves, as a prelude to pressing, has the advantage that leaf protein, in a form suitable for use as food for non-ruminant animals including man, is made as a by-product. This aspect of the technological use of leaves has been discussed elsewhere [8] and need not be considered here. It will probably be more economical to heat leaves in bulk rather than poison them. What would then be needed is a press in which material that had been heated to about 70° C. can be exposed to about 6 kg. per cm.^{2} for a few seconds, if the layer is only 1 cm. thick, but for longer if the layer is thicker. The dry matter content can thus be raised to 40-50 per cent. Presses suitable for this process are already in use for de-watering peat, but the fibrous nature of most leaves makes it possible to use much simpler presses.

An alternative possibility is to ferment the crop by the methods used in sewage disposal so as to make methane. Here the separation of the combustible material from water is exceptionally easy because methane has such a low solubility. Furthermore, only the C and H of the crop are burnt; all the P and K and almost all the N remain in the fermentation tank and are ready for use again as fertilizers. This conservation of N gives fermentation a very great advantage over direct burning, especially when intensive production is undertaken.

The overall reactions can be idealized as:

$$CO_2 + H_2O \;\; \textit{light} \;\; (HCOH) + O_2$$
$$2(HCOH) \;\; \textit{fermentation} \;\; CH_4 + CO_2$$
$$CH_4 + 2O_2 \;\; \textit{combustion} \;\; CO_2 + 2H_2O$$

Methane fermentation has two defects. It is slow; a tank produces only a fifth of its volume of gas per day over the whole fermentation period, though for a short time it produces its own volume each day. There is good reason to think that with adequate research, and with selection of thermophilic fermenting organisms, the process could be run more rapidly at a higher temperature. Methane is a convenient product for use beside the fermenter, but high pressure cylinders are needed if it is to be used on a tractor. This difficulty would be overcome if the fermentation were varied to make alcohol or acetic acid, but then the great merit of methane, that it separates from water without effort, would be lost. The ideal fermentation would produce a water-immiscible combustible material e.g. a hydro-carbon, higher alcohol or fat; but this is not an immediate prospect.

The convenience of electricity and of liquid or gaseous fuels when small engines are being run on the farm has diverted attention from the possibilities of designing a gas turbine, or even a diesel, that could be fed on farm wastes rammed directly into the combustion region. This would combine efficiency with the draught animal's merit, that it can be wholly maintained by the farm on which it works, and would be a great advantage in countries short of fossil fuel.

In 1952 a committee of the British National Physical Laboratory [6] concluded that plant growth was the most promising method for collecting solar energy. Since then there have been improvements in some of the other proposed methods but, in spite of this improvement, it is still probable that several aspects of plant growth would repay intensive research. Although the committee considered the possibilities of using algal photosynthesis it attached most importance to wood as a fuel, and suggested that average requirements for pumping water in India would be satisfied if a fiftieth of the area to be irrigated were dedicated to fuel production. Today farm wastes contribute 3.2×10^{12} kwh. and wood only 1.4×10^{12} to a world total power consumption of 25×10^{12} kwh. per year [10]. I consider that the fraction of the total that is made up from farm wastes could with advantage be increased and that farming could be to some extent re-organized with this in mind.

Most improvements in farming technique are designed to maintain a fuller photosynthetic cover over the land for a larger proportion of the year, so that less light falls ineffectively on bare ground. A limit is set by the encouragement that the maintenance of optimal conditions gives to leafy vegetative growth at the expense of the seeds and tubers that the farmer normally wants. When the leaf becomes more of an asset this feature of plant physiology will become less troublesome. High productivity farming has hitherto been dependent on abundant water supplies so that an extra-terrestrial visitor, studying a map showing the density of population, might well conclude that man is an amphibian. The rapid increase in world population will soon make us try to get more food from arid areas of abundant sunlight and, while this is being done, the possibilities of also getting power should be borne in mind.

Jonathan Swift, jeering at what he regarded as the foolish and impractical pursuits of the Royal Society of his day, had one of the inmates of the Academy of Lagado "eight years upon a project for extracting sunbeams out of cucumbers, which were to be put into phials hermetically sealed, and let out to warm the air in raw inclement summers". I am aware that my own enthusiasm for the plant may seem similarly obsessional. But the Lagadian may have had the germ of a good idea though he was not necessarily correct in choosing the cucumber as a vehicle for it.

APPENDIX

Some relevant quantities and relations.

Surface area of the earth: 5.1×10^{14}m.^{2}.

Solar radiation at earth's surface on an average cloudless day with sun near zenith:

$$1 \text{ kw./m.}^2 = 1.4 \text{ cal./cm.}^2 \text{ min.}$$

Average CO_2 content of atmosphere around a crop during the day: 0.025 volumes per cent = 0.5 mg./l. alternatively 0.11 g. carbon per cm.^{2}.

Heats of combustion: Coal 8 kil.-cal./g. or 10,000 kwh./ton wood and other carbohydrates 4-5 kil.-cal./g. or 5,000 kwh./ton.

1 kwh. = 1.36 h.p. hours = 3410 B.Th.U. = 860 kil.-cal. = 3.6 M joules.

1 ton per acre = 2.5 metric tons per hectare.

LES FEUILLES, SOURCE D'ÉNERGIE

par

N. W. Pirie

RÉSUMÉ

Il y a trois catégories de matières végétales à considérer : les résidus existants, ceux que l'on obtiendrait en apportant certaines modifications aux modes de production des denrées alimentaires et les plantes délibérément cultivées en tant que sources d'énergie. Celles-ci font directement concurrence aux divers appareils qui ont eux aussi pour objet d'utiliser l'énergie solaire (moteurs à chaleur solaire, cellules photo-électriques, etc.) et leur culture n'offrirait vraisemblablement plus d'avantages si l'on arrivait à élever à 10 % le rendement de ces appareils.

La photosynthèse naturelle a un rendement d'environ 0,2 % et de bonnes méthodes agricoles permettent d'obtenir un rendement de 2,4 %. Avec de grandes quantités d'eau, on peut doubler ce chiffre, mais à l'heure actuelle il est impossible d'y arriver lorsque l'eau est rationnée. La plupart des plantes gaspillent d'énormes quantités d'eau, mais on a toutes raisons de penser que, partout où d'autres éléments nutritifs sont présents et où l'eau, bien que peu abondante, arrive régulièrement, on devrait pouvoir développer la culture d'espèces beaucoup plus économiques.

Les matières résiduelles traditionnellement employées comme combustibles proviennent soit de tissus secs et ligneux, soit d'éléments végétaux séveux qu'on a laissés sécher par terre. Il faut renoncer à la production des unes et des autres si l'on veut donner à la photosynthèse son rendement maximum ; car pour cela il faut que le sol demeure recouvert le plus longtemps possible d'une verdure luxuriante. On obtient ainsi une masse incombustible de feuilles qui doivent être traitées avant de pouvoir servir à faire du feu. On peut, après une préparation appropriée, en extraire de l'eau ; et cette opération peut se combiner avec la fabrication de protéine végétale, qui constitue un aliment précieux pour l'homme et pour certains animaux non ruminants. Les résidus humides de ces différentes opérations peuvent être séchés pour servir de combustible, mais il serait beaucoup plus satisfaisant de les faire fermenter afin d'en tirer du méthane et, si possible, des hydrocarbures plus complexes. Cette dernière méthode présente trois avantages : elle préserve l'azote des plantes, qui pourra servir d'engrais pour la récolte suivante ; les hydrocarbures sont, en raison de leur insolubilité dans l'eau, particulièrement faciles à séparer du mélange en fermentation ; enfin, les combustibles fluides sont bien préférables aux matières fibreuses, qui tiennent beaucoup de place.

Il n'y a pas lieu de penser que d'autres végétaux pourraient, comme producteurs de matières alimentaires ou de combustibles, donner de meilleurs résultats que les plantes supérieures du type de celles dont la culture est déjà courante. Dans des circonstances spéciales, il pourrait y avoir avantage à utiliser des algues unicellulaires, notamment celles qui vivent dans l'eau salée et celles qui sont capables de fixer l'azote ; mais les nombreux travaux qui ont été consacrés aux chlorelles semblent mal conçus.

Pour que ces projets puissent prendre forme sur le plan pratique, il faudra encore bien des recherches ; et il conviendrait d'entreprendre ces recherches avant que l'épuisement des combustibles fossiles ne rende la question urgente. Nous sommes d'autant plus enclins à penser de la sorte que la quantité de carbone en circulation est appelée à augmenter en raison de l'épuisement des combustibles fossiles, ce qui sera nettement favorable au développement de la végétation.

LA ENERGÍA EXTRAÍDA DE LAS HOJAS

por

N. W. Pirie

RESUMEN

Hay que tener en cuenta tres fuentes vegetales de energía: los actuales desperdicios vegetales, los residuos que se obtendrían si se introdujeran ciertos cambios en los métodos de producción de alimentos, y los productos vegetales cultivados expresamente para utilizarlos como fuentes de energía. Esta última está en competencia directa con otras formas de aprovechamiento de la energía solar, como los aparatos heliocaloríferos y las fotocélulas; es improbable que ofrezcan ninguna ventaja si la eficiencia de aquéllos puede aumentarse hasta un 10 %.

La fotosíntesis natural tiene una eficacia de un 0,2 % aproximadamente y un buen método agrícola viene a dar un 2,4 %. Con un buen suministro de agua esas cifras pueden llegar a doblarse, pero en la actualidad no es factible conseguir esas cifras donde el riego es escaso. La mayoría de las plantas consumen enormes cantidades de agua, pero todo hace pensar que si pueden procurárseles otras materias nutritivas y en tanto que se les pueda suministrar una pequeña cantidad de agua, será posible obtener variedades mucho más económicas.

Las materias no aprovechadas y los residuos que se utilizan tradicionalmente como combustible son o bien partes secas y leñosas o partes jugosas de las plantas que se han marchitado y perecido. Tanto unas como otras deben dejar de producirse si buscamos la máxima eficiencia fotosintética para la que es necesario mantener una jugosa capa verde en el suelo el mayor tiempo posible. El resultado es una masa de hojas incombustibles que necesita una preparación antes de que pueda utilizarse como combustible. Las hojas se someten a apropiados tratamientos previos, eliminándose luego el agua, operación que puede combinarse con la producción de proteína vegetal que constituye un alimento valioso para el nombre y para los animales no rumiantes. El residuo húmedo de estos procesos podría secarse para producir así el combustible, pero es mucho más práctico hacerlos fermentar para obtener gas metano o, de ser posible, hidratos de carbono superiores. Con ello se obtendrían tres ventajas: el nitrógeno de la planta se conservaría para ser utilizado como abono en la próxima cosecha ; debido a su insolubilidad en el agua, la separación de los hidratos de carbono de la mezcla de fermentación es sumamente fácil: los flúidos son combustibles más satisfactorios que los voluminosos materiales fibrosos.

No existe ningún motivo para creer que otras plantas podrían producir más eficazmente alimentos o combustibles que las plantas superiores del tipo general ya utilizado en la agricultura. En circunstancias especiales serían útiles las algas unicelulares, particularmente las que viven en agua salada y las que pueden fijar el nitrógeno, pero la gran cantidad de trabajos realizados con la especie *Chlorella* no parecen haber producido los resultados esperados.

Aún habrá que realizar muchos estudios antes de que estas propuestas lleguen a tener carácter práctico. Pero habrá que realizarlos rápidamente antes de que la extinción de los combustibles fósiles dé mayor urgencia a este problema. Nuestra confianza en que ésta es una forma razonable de enfocar la cuestión es aún mayor debido al hecho de que el aumento de la cantidad de carbón circulante, que será una consecuencia de la extinción de los combustibles fósiles, estimulará en forma considerable el crecimiento vegetal.

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DISCUSSION

Mr. **Ramdas**. With regard to dew, the Central Agricultural Meteorological Observatory at Poona has been investigating the variation of this phenomenon with season and with height above ground with the aid of a series of Duvdevani dew gauges exposed from ground level up to 35 ft. above ground. Dew is deposited on a surface exposed to the sky when, owing to radiative cooling, it attains a temperature less than the dew-point. It is found that dew fall at Poona is confined to the early and late weeks of the clear winter season and attains a maximum value a few feet above the ground surface, decreasing rapidly as one goes up higher. The coastal regions of India receive more dew fall than the interior regions, where the specific humidity is often too low and at the same time exposed objects fail to attain sufficiently low temperatures by radiative cooling and so remain above the dew-point.

Even when there is no dew fall on clear nights there is considerable "invisible condensation" on the soil surface as well as on hydroscopic objects lying in the open. These surfaces evaporate or give up moisture under the influence of insolation warming from the minimum to the maximum temperature epoch. During the afternoon (after the maximum temperature period) invisible condensation begins and continues throughout the night and until the minimum temperature period next morning. This phenomenon, viz. the *upward* movement of water vapour during a part of the day and *downward* movement of water vapour during the late afternoon, evening and night is a daily feature and is associated with negative and positive vertical gradients of the vapour pressure. This exchange is most conspicuous in the black cotton soil areas, less so in the red soil areas and least in the Indo-Gangetic alluvial areas.

It is problematic how far living plants utilize dew and invisible condensation as secondary sources of moisture and much critical research is desirable on this interesting subject, particularly in the arid zones.

Mr. **Daniels**. In connexion with the use of plant material for fuel, gas research on fuel cells might well be encouraged. It is possible to heat organic material with a small amount of air with a catalyst and obtain carbon monoxide and hydrogen. This synthesis gas can be bubbled over one electrode in a fused salt bath and air bubbled over the other electrode. In this way it is theoretically possible to convert the energy of the oxidation directly into electricity in an electro-chemical cell. Laboratory work has been started in Holland, England and the U.S.A. Much research will be needed before anything practical and economical can be expected.

NOTE SUR LES ÉTUDES ET TRAVAUX D'ANDRÉ NIZERY

concernant l'énergie thermique des mers, la production concomitante d'eau douce et l'utilisation éventuelle préalable de bassins de chauffage solaire

par

M. Beau

André Nizery est décédé le 27 février 1954 à l'âge de quarante-six ans. Il était membre du Comité consultatif de recherches sur la zone aride de l'Unesco et avait occupé au cours de sa carrière les fonctions très diverses et souvent simultanées de directeur des travaux du port de Dakar, secrétaire général puis administrateur de l'Office de la recherche scientifique coloniale, directeur général de la Société hydrotechnique de France, directeur adjoint du Service des études et recherches de l'Électricité de France, directeur du Laboratoire national d'hydraulique de Chatou, professeur d'hydraulique à l'École nationale des ponts et chaussées.

ÉNERGIE THERMIQUE DES MERS

Voyons tout d'abord les points principaux sur lesquels s'est exercée l'action de M. André Nizery en matière d'énergie thermique des mers.

Georges Claude, qui avait eu le très grand mérite de montrer que le principe n'était pas utopique et même de réussir à faire tourner pendant quelques jours une petite turbine de démonstration à Cuba, avait toutefois abandonné la partie en laissant bien des points dans l'ombre.

Parmi ces points, une première question essentielle et préalable : si l'on pompe en mer de l'eau froide à grande profondeur, et avec les débits de plusieurs mètres cubes par seconde que nécessite cette technique, qui fait intervenir forcément de gros débits en contrepartie des faibles écarts de températures possibles, que va-t-il se passer au sein de la mer dans la zone intéressée par les pompages ? Ne va-t-il pas y avoir, à la longue, un brassage général montant jusqu'en surface de telle sorte que la température des eaux pompées ne corresponde plus qu'à une moyenne, et que l'écart de température sur lequel on se fonde s'évanouisse pratiquement ?

On pouvait bien pressentir que ce brassage, dans les conditions d'opération, ne se produirait probablement pas, mais il fallait le démontrer d'une façon péremptoire de telle manière qu'un projet de réalisation à grande échelle ne puisse sur ce point essentiel comporter une part d'aventure. Tel fut l'objet des première recherches qui furent menées avec le concours précieux du célèbre laboratoire des ateliers Neyret-Beylier et Piccard-Pictet à Grenoble.

Or ces recherches, conduites à la fois sur le plan théorique et en modèle réduit permirent, avec une coïncidence remarquable, de mettre en lumière la loi physique qui règle d'une façon très étroite le jeu des écoulements dans une nappe d'eau à densité progressivement croissante en fonction de la profondeur lorsque la prise d'eau est profonde et que sa section est faible par rapport à la hauteur d'eau intéressée.

Cette loi physique se traduit par la formule :

$$\frac{gh^5}{q^2} \times \frac{\Delta\rho}{\rho} = \text{constante}$$

dans laquelle ρ est la densité à la partie supérieure du liquide, $\Delta\rho$ sa différence de densité avec le liquide inférieur, g l'accélération de la pesanteur, q le débit et h la hauteur limite d'aspiration c'est-à-dire en fait la demi-épaisseur de la couche aspirée.

En poussant plus loin l'étude et en faisant intervenir la notion de gradient de densité sous la forme plus imagée de la hauteur théorique H d'où il faudrait s'enfoncer à partir de la prise d'eau pour voir doubler la densité, on peut affirmer maintenant que l'épaisseur de la couche aspirée sera inférieure à :

$$E = 0{,}68 \times 0{,}04 \quad 0{,}787 \left(\frac{q}{H^2 \sqrt{H}}\right)^{0{,}212} \times H.$$

Pour prendre un exemple, la hauteur H étant égale à Abidjan à 800.000 d'après les mesures du gradient de densité, une centrale de 50.000 kW qui aspirerait 80 m^3/s à plus de 400 m de profondeur ne ferait intervenir qu'une tranche horizontale d'eau ne dépassant jamais 39 mètres en dessus ou en dessous de la prise.

On trouve d'ailleurs dans les différentes études sur l'énergie thermique des mers qui ont paru sous la signature de M. Nizery [1,3][1] des développements plus détaillés sur cette question dont nous ne retiendrons que la conclusion générale en ce qui concerne l'énergie thermique des mers, à savoir que dans les conditions de débit pratiquement envisageables il n'y a aucun risque qu'un brassage dangereux puisse se produire, la marge de sécurité au-delà de laquelle le phénomène de brassage dangereux commencerait à se produire étant même considérable.

Parmi les autres questions sur lesquelles M. Nizéry a fait porter les études qu'il dirigeait, il faut citer principalement : *a*) le choix du cycle de fonctionnement et du mode de construction de cette singulière machine thermique qui ne dispose que d'une chute de température de 20° environ *b*) la recherche et le choix du meilleur dispositif d'évaporateur de l'eau chaude ; *c*) le problème de la condensation qui pose la question de l'eau douce comme sous-produit ; *d*) la recherche et le choix du meilleur type d'extracteur des gaz dissous ; *e*) l'étude et le choix de la meilleure conception à envisager pour aller chercher les eaux froides des profondeurs, soit par une conduite posée sur les fonds sous-marins, soit par un tunnel souterrain débouchant sous la mer à la profondeur voulue, soit par une conduite verticale dans le cas d'une centrale sous-marine placée en eau calme à faible distance de la surface — l'étude concluant au moins pour les premières réalisations en faveur de la conception "conduite posée sur les fonds sous-marins" ; *f*) la recherche des dispositifs les plus appropriés pour la pose par mer houleuse de la conduite d'eau froide à grande profondeur, ce problème se décomposant à son tour en études, d'une part du matériel de pose, et d'autre part des procédés assurant la souplesse de la conduite pour épouser les formes des fonds sous-marins.

Donnons quelques indications sur ces études :

L'étude sur le cycle de fonctionnement a montré notamment que le choix des différences de température à l'entrée et à la sortie du condenseur et de l'évaporateur n'était pas libre. Elle a également permis de déterminer avec une bonne approximation la puissance récupérable en fonction des quantités d'eau chaude et d'eau froide, et de la différence globale de température disponible. L'analyse plus poussée du problème a conduit à la conception d'un cycle à condensations et évaporations en étages qui permet de majorer considérablement la puissance qui serait disponible avec un cycle à simple évaporation et à simple condensation.

En ce qui concerne l'évaporateur, M. Nizery, pressentant que le rendement varierait très sensiblement suivant le dispositif que l'on pouvait envisager, fit procéder à des essais comparatifs à une échelle semi-industrielle dans l'ancienne usine élévatoire de Bercy. Les publications citées précédemment donnent de multiples précisions sur les dispositifs essayés (écoulement en lame mince sur un plan incliné, faisceau de jets d'eau verticaux, dispositifs "en pluie", évaporateur en nappe épaisse, etc.). Ces essais établirent que les pertes d'énergie, tant sur l'eau que sur la vapeur, étaient minimales lorsque l'on faisait arriver l'eau en jets verticaux par des séries d'ajutages à section rectangulaire.

Le problème de la condensation présente du point de vue de la production de l'énergie une importance beaucoup moindre du fait que les débits d'eau intéressés y sont bien moins grands qu'à l'évaporation et que, par conséquent, l'amélioration que l'on pourrait apporter par des dispositifs plus compliqués inspirés par exemple de machines frigorifiques serait difficilement rentable. On a donc été conduit à proposer l'adoption d'un condenseur par mélange dont la construction et l'entretien très simples constituent des avantages non négligeables dans la pratique.

M. Nizery toutefois n'a pas perdu de vue que, dans certains cas où la production d'eau douce peut être particulièrement souhaitable, voire même vitale, l'adoption d'un condenseur à surface, par exemple du type faisceaux tubulaires en métal peu oxydable tel que le métal Monel, permettrait d'obtenir de l'eau douce en quantités considérables.

Une étude a montré que ces faisceaux tubulaires pouvaient être facilement placés dans l'enceinte de la centrale ; d'autre part, les investissements supplémentaires rendus nécessaires permettaient toutefois d'obtenir de l'eau douce pour un prix de revient qui, en première approximation, était déjà inférieur de moitié au prix de l'eau extraite des centres de captage d'une grande ville coloniale qui avait été prise comme terme de comparaison.

On peut donner une idée des quantités d'eau douce susceptibles d'être produites en disant que la quantité d'eau produite par une centrale d'énergie thermique des mers, d'une capacité suffisante pour satisfaire à elle seule les besoins en énergie d'une ville déterminée, serait suffisante également pour assurer dans des conditions normales le ravitaillement de cette ville en eau douce. Par exemple, si cette centrale suffisante avait 10.000 kW de puissance, elle pourrait donner également 15.000 m^3 d'eau douce par jour.

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[1] Les chiffres entre crochets renvoient à la bibliographie, à la fin de ce rapport.

Le problème des gaz dissous fut l'une des objections majeures qui opposèrent G. Claude à ses contradicteurs lors de ses premières recherches. Les 25 à 30 cm^3 de gaz contenus dans chaque litre d'eau chaude produisent en effet un volume très important à évacuer dès que l'on considère des débits d'eau chaude de plusieurs mètres cubes par seconde. Avec les anciens extracteurs d'air de rendement très faible, on pouvait prétendre que l'extraction des gaz dissous absorberait plus que la puissance produite. G. Claude répondit à ces objections en faisant réaliser par la maison Rateau un extracteur d'air rotatif qui donna un rendement de 65 %, résolvant déjà le problème dans sa conception générale.

L'étude fut reprise par M. Nizery, d'une part sur le plan théorique, et d'autre part au moyen d'essais effectués au Laboratoire national d'hydraulique de Chatou. Avec les dispositions finalement adoptées, on a la certitude que l'extracteur des gaz dissous n'absorbera pas plus de 6 à 7 % de la puissance brute produite.

La question de la conduite d'alimentation en eau froide sous-marine est une des questions capitales du problème de l'énergie thermique des mers.

G. Claude avait préconisé et essayé au début le type "conduite posée sur les fonds sous-marins avec usine à terre". Il a essayé ensuite le type "conduite verticale accrochée à une usine flottante", en l'espèce le bateau *Tunisie*, et il avait finalement proposé au gouvernement, après les difficultés rencontrées pour le raccordement d'une conduite verticale immobile en profondeur avec une installation de surface ballottée par la houle, d'essayer un troisième type constitué par une usine à terre reliée aux grands fonds sous-marins par un tunnel débouchant sous l'eau à la profondeur voulue.

Cette dernière proposition, après étude approfondie, a été écartée comme extrapolant de façon actuellement trop risquée les résultats du même genre obtenus dans certains équipements hydro-électriques pour les prises d'eau au fond des lacs, car il s'agit de passer de techniques éprouvées pour des profondeurs d'eau de l'ordre de 30 mètres à une adaptation à des profondeurs de plus de 400 mètres, c'est-à-dire comportant des pressions près de quinze fois plus fortes. Il a donc semblé plus sage de commencer par le type "conduite posée sur les fonds sous-marins" dont les aléas paraissaient moindres *a priori* et sur la conception duquel Georges Claude, malgré ses déboires, avait réussi néanmoins une expérience positive puisqu'il avait fait tourner pendant onze jours son usine de démonstration.

M. Nizery resta toutefois d'avis, après étude de la question, que le type d'avenir serait celui de la centrale sous-marine en eau calme, à une vingtaine de mètres de la surface, avec conduite verticale pour l'alimentation en eau froide, car, d'une part, cette conduite sera très courte (quelques centaines de mètres au lieu de plusieurs kilomètres), et, d'autre part, le champ d'application de l'énergie thermique des mers deviendra pratiquement illimité. On pourra toujours en effet trouver les fonds nécessaires en s'éloignant des côtes, la question du transport de l'énergie produite se résolvant facilement par un câble sous-marin, tandis que pour le type "usine à terre" l'installation de centrales d'énergie thermique des mers est conditionnée par l'existence de points favorables des côtes tropicales où les eaux froides des profondeurs s'approchent suffisamment de ces côtes grâce à la présence de vallées sous-marines. Or, ces points favorables sont forcément en nombre limité.

C'est au problème de la pose en mer de la grande conduite d'alimentation en eau froide que M. Nizery a consacré ses recherches les plus poussées, ainsi que d'importants essais en mer dont certains se poursuivent encore.

Après de nombreuses études portant sur les diverses solutions possibles de ce problème, M. Nizery est arrivé à la conviction que pour être maître à tout moment de la manœuvre dans une mer sujette à une légère houle, il fallait supporter la conduite jusqu'à sa mise en place par des engins quasi insensibles à la houle si l'on ne voulait pas risquer d'accidents entre ces engins oscillant dans la houle et la conduite se déplaçant en eau calme à partir d'une certaine profondeur ; d'où son idée de flotteurs antihoules entièrement de sa conception et dont les brevets portent son nom.

Ces engins, constitués essentiellement par des cylindres métalliques creux situés à quelques mètres sous l'eau et supportant, par des montants verticaux, une plate-forme de manœuvre placée au-dessus de l'eau, furent essayés avec succès une première fois au large de Brest par des houles de 2 à 3 mètres de creux, puis, sous une forme plus perfectionnée, au large d'Abidjan. Les essais ont comporté l'étude d'une série de manœuvres d'un intérêt indiscutable, mais toutefois secondaire par rapport à celui de la conception générale, et sur lesquelles il serait trop long de s'étendre.

La deuxième question essentielle à résoudre était la manière d'assurer la souplesse d'une conduite d'environ 2 mètres de diamètre, tant pour épouser les formes des fonds sous-marins que pour permettre les transports, les manœuvres et la mise en place. Pour obtenir la souplesse nécessaire, G. Claude avait utilisé des conduites en tôle ondulée. Ce procédé ne pouvant constituer une solution définitive en raison des pertes de charge causées par les ondulations, M. Nizery estima que la solution devait être recherchée dans la mise au point de joints souples séparant des éléments rigides ; il étudia donc un premier type de joint souple qui fut essayé au large de Brest, puis un deuxième qui se présente sous la forme d'un élément de conduite en caoutchouc armé. Ces derniers joints démontrèrent victorieusement leurs qualités au cours des récents essais d'Abidjan, ce qui permet d'affirmer que le problème de la souplesse est entièrement résolu.

En dehors des points principaux mentionnés plus haut, M. Nizery s'est penché sur de multiples points secondaires que nous ne ferons qu'énumérer : l'étude hydrographique et océanographique des fonds au voisinage d'Abidjan, les moyens les plus appropriés pour franchir la très forte barre de déferlement de la houle sur la côte, l'étude de l'étanchéité thermique de la conduite, l'étude de l'étanchéité de la centrale, qui est en dépression, la lutte contre la corrosion et les encrassements, les systèmes de repérage en mer, l'étude de la turbine et de l'alternateur, l'étude économique du prix de revient, l'étude des aires géographiques favorables, enfin l'étude des sous-produits possibles en sus de l'eau douce : eaux fraîches résiduelles pour la climatisation ou l'industrie, fabrication de sel marin et industries chimiques, etc.

ÉNERGIE SOLAIRE

La puissance d'une centrale d'énergie thermique des mers étant en gros proportionnelle au carré de l'écart de température entre l'eau froide et l'eau chaude, M. Nizery a pensé qu'il serait intéressant de rechercher si l'on ne pourrait pas augmenter le rendement des centrales en surchauffant préalablement l'eau chaude, par une exposition au soleil dans des conditions appropriées.

Déjà il avait observé que la température de l'eau de la lagune d'Abidjan, eau plus ou moins stagnante et en couche mince, était supérieure de 2 à 3^{o} à celle de la surface de la mer ; d'où la disposition adoptée pour Abidjan, consistant à aller chercher l'eau chaude dans la lagune.

Pour aller plus loin dans cette voie, il a fait étudier dans des bassins artificiels à Dakar, et sous la direction très éclairée du professeur Masson, les divers moyens de relever dans des conditions d'investissements peu onéreuses la température de l'eau s'écoulant en lames minces dans ces bassins exposés au soleil, la couche superficielle de l'eau étant protégée par une pellicule solide ou liquide pour empêcher l'évaporation, source de refroidissement, tout en laissant passer les calories.

Nous n'insisterons pas sur le détail des multiples essais entrepris avec de l'huile, des vitres, des bacs métalliques, etc., combinés ou non, essais qui sont d'ailleurs encore loin d'être terminés, M. Masson ayant exposé lui-même le détail de ses divers essais, dans leur état actuel.

Disons simplement que M. Nizery paraît avoir posé le problème de l'énergie solaire sous un jour nouveau, car jusqu'ici il n'apparaissait guère possible de le résoudre sur un plan économiquement rentable autrement que pour des applications particulières telles que : production de hautes températures pour la fusion de certains corps, production du froid, production d'eau chaude à l'échelle domestique, production d'eau douce à petite échelle.

On pouvait, pensa-t-il, espérer une solution rentable en combinant l'énergie solaire avec l'énergie thermique des mers ou même, éventuellement, en faisant marcher directement des centrales à dépression, de type analogue, sur un écart de température qui serait uniquement dû au surchauffage solaire, ce qui conduisait pratiquement au problème de l'énergie solaire à l'état pur.

L'idée générale mise en avant est en somme celle de la captation et de la conservation, puis de l'utilisation des calories solaires, à basse température, en mettant en jeu des grandes masses fluides et des surfaces étendues (le terrain ne coûtant pas cher dans les régions arides) ainsi que des investissements au mètre carré aussi faibles que possible, car l'étude a fait ressortir qu'il existe à cet égard des conditions limites à observer. Dans le cadre de cette idée générale l'exploration paraît pouvoir être avantageusement poursuivie sur deux voies, assez voisines d'ailleurs : celle d'un gain relativement faible de température avec des moyens très peu coûteux, et celle d'un gain plus sensible avec un investissement plus onéreux, grâce par exemple à des appareils du type "lame mince d'eau entre deux tôles et sous châssis vitré, avec contact de l'air chaud en dessus et en dessous des tôles" qui a été récemment étudié par M. Masson.

Nous donnons plus loin une bibliographie des publications faites par M. Nizery sur la question de l'énergie thermique des mers, et nous terminerons en exprimant notre immense regret personnel que la carrière de M. Nizery ait été si prématurément interrompue au moment où l'aboutissement de ses idées, recherches, études et essais divers, dans les domaines que nous avons passés en revue, était en si bonne voie et paraissait susceptible d'assurer définitivement à l'humanité la conquête de nouvelles sources d'énergie, si difficiles à capter.

MEMORANDUM

on studies and research conducted by André Nizery on the thermal energy of sea water, the concomitant production of fresh water and the possible preliminary utilization of solar heating tanks

by

M. Beau

Chairman, Société "Énergie des mers"

SUMMARY

André Nizery died on 27 February 1954 at the age of 46. He was a member of the Unesco Advisory Committee on Arid Zone Research and in the course of his career had held—often concurrently—appointments as diverse as director of works, Port of Dakar; secretary general, and later administrator, Office de la recherche scientifique coloniale (Colonial Scientific Research Office); director-general of the Société hydrotechnique de France (Hydraulic Engineering Company); assistant director of the Service des études et recherches of Électricité de France; director of the Laboratoire national d'hydraulique (National Hydraulics Laboratory) at Chatou and professor of hydraulics at the École nationale des ponts et chaussées.

THERMAL ENERGY OF SEA WATER

Georges Claude, to whom much is owed for having shown that the principle was not impracticable and for having even succeeded in operating a small demonstration turbine for a few days in Cuba, was nevertheless obliged to give up; without being able to throw light on many points which, to the critically minded, remained obscure.

Mr. Nizery first of all tackled and solved the problem of the possible risk, during pumping operations, of a mixing of the cold water from the depths of the sea with the warm surface water. Experimental work on this subject, conducted with the invaluable assistance of the Laboratoire des Ateliers Neyret-Beylier et Piccard-Pictet at Grenoble, revealed a physical law linking up the cold water discharge, the density and the density gradient of the sea water with the depth and the maximum thickness of the sheet of cold water sucked in at the bottom of the sea. The conclusion is that, in normally practicable discharge conditions, there is no danger of mixing at all.

Among the other points of primary importance upon which Mr. Nizery focused his research, without counting studies of many secondary problems, were: choice of the working cycle of the power plant which has a temperature difference of only about 20°, choice of the best evaporator, problem of condensation, which makes it possible to obtain massive quantities of fresh water as a by-product, extraction of dissolved gas in order to maintain the depression in the power plant, choice of possible methods of pumping cold water from the sea at great depth pending the production of future floating submarine power plants, study of the best way of laying a pipeline with flexible joints, using anti-swell floats, specially designed for the purpose by Mr. Nizery.

SOLAR ENERGY

As the power of a marine thermal energy plant is roughly proportional to the square of the difference in temperature between cold and warm water, Mr. Nizery rapidly came to the conclusion that it would be interesting to find out whether the efficiency of power plants could not be increased by a preliminary superheating of the warm surface water by the sun's rays in appropriate conditions.

Studies on this subject, carried out in artificial basins at Dakar with the extremely enlightened assistance of Mr. Masson, a professor of physics, who has himself reported on this question, presented the problem of solar energy in a new light.

Mr. Nizery was convinced that the problem of solar energy could be solved in a profitable way by collecting and utilizing solar heat at a low temperature, large volumes of liquid and extensive surfaces equipped as cheaply as possible being brought into play.

This idea can, of course, be combined very well with the concept of a marine thermal energy plant, but there is also a possibility of having independent temperature difference plants, powered only on the temperature difference created by the solar super.heating tanks, and it is a matter of deep regret that Mr. Nizery's career should have come to such an abrupt and premature end, just when his plans, so full of promise for mankind, were about to materialize.

NOTA

sobre los estudios y trabajos de André Nizery sobre la energía térmica de los mares, la producción concomitante de agua dulce y la posible utilización de depósitos de calentamiento solar

por

el Sr. Beau

RESUMEN

El Sr. André Nizery falleció el 27 de febrero de 1954 a la edad de cuarenta y seis años. Era miembro del Comité Consultivo de la Unesco de Investigación sobre la Zona Árida y había ocupado en el curso de su carrera las funciones muy diversas y a menudo simultáneas de director de los trabajos del puerto de Dakar, secretario general, luego administrador, de la Oficina de Investigación Científica Colonial, director general de la Sociedad Hidrotécnica de Francia, director adjunto del Servicio de los Estudios e Investigaciones de Electricidad de Francia, director del Laboratorio Nacional de Hidráulica de Chatou, profesor de hidráulica en la Escuela Nacional de Caminos, Canales y Puertos.

LA ENERGÍA TÉRMICA DE LOS MARES

G. Claude, a quien corresponde el mérito de haber mostrado que este principio no es mera utopía y quien consiguió hacer funcionar durante unos días una pequeña turbina experimental en Cuba, había abandonado estos trabajos dejando sin aclarar numerosos problemas.

A. Nizery se dedicó primeramente a resolver el problema que planteaba el riesgo de la mezcla de las aguas frías de las profundidades con las aguas templadas de la superficie como consecuencia del bombeo. La conclusión de sus estudios sobre este punto, realizados con la utilísima colaboración del Laboratoire des Ateliers Neyret-Beylier et Piccard-Pictet, de Grenoble, ha permitido establecer una ley física que relaciona el caudal del bombeo de agua fría, la densidad y el gradiente de densidad del agua marina con la profundidad y el espesor máximos de la capa de aspiración del agua fría en las profundidades. De esa ley se deduce que el riesgo mencionado es nulo en el caso de los caudales prácticamente obtenibles.

Nizery estudió también, aparte de otros problemas secundarios, los puntos principales siguientes: elección del ciclo de funcionamiento de una central térmica que no dispone más que de un margen de temperatura de unos 20°; elección del evaporador más eficaz; el problema de la condensación, que supone la posibilidad de obtener grandes cantidades de agua dulce como un subproducto; extracción de los gases en disolución a fin de mantener la depresión en la central; elección de los mejores sistemas para el bombeo de las aguas frías de las grandes profundidades hasta tanto se establezcan las centrales flotantes del futuro; estudio del tendido racional de un conducto provisto de juntas flexibles a base de estabilizadores antimarea inventados y perfeccionados por el Sr. Nizery.

ENERGÍA SOLAR

Como la potencia de una central de energía térmica derivada del mar es función del cuadrado de la diferencia de temperatura entre el agua fría y la caliente, el Sr. Nizery, echó de ver rápidamente la conveniencia de aumentar el rendimiento de las centrales recalentando previamente el agua caliente mediante su isolación en condiciones apropiadas.

Los estudios realizados en ese sentido en los depósitos artificiales de Dakar, con el inteligente concurso del profesor Masson, a quien hemos tenido el honor de escuchar personalmente una comunicación sobre este tema, han transformado por completo el planteamiento del problema de la energía solar.

El Sr. Nizery había llegado a la conclusión de la posibilidad de la explotación económica de la energía solar mediante un sistema de captación y utilización de las calorías solares a baja temperatura, haciendo uso para ello de grandes superficies líquidas provistas del equipo más económico posible.

Esta noción se combina perfectamente con la concepción de una central de energía térmica marítima, pero también es posible prever centrales autónomas que funcionen a depresión, haciendo uso únicamente de la diferencia de temperatura creada en los depósitos de supercalentamiento solar. Por ello es muy de lamentar que la carrera del Sr. Nizery haya quedado tan cruel y prematuramente truncada en el momento en que tomaban concreción esperanzas de tanto interés para la humanidad.

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Discours prononcés lors de la séance finale du colloque, le 26 octobre 1954

Discours de

A. V. Baum

Monsieur le président, Mesdames et Messieurs,

Nous avons entendu une série d'intéressants rapports sur l'exploitation des sources permanentes de l'énergie. Ces rapports confirment une fois de plus que ces travaux sont utiles, et même indispensables. Des expériences et des calculs exacts et dignes de foi montrent que, dans beaucoup de cas, cette exploitation est, dès à présent, avantageuse et rentable. Il faut absolument mettre au point des appareils permettant de transformer l'énergie solaire et l'énergie éolienne en d'autres formes d'énergie, et élaborer des plans en vue de leur utilisation. Il importe d'entreprendre la production en série de ces appareils. C'est surtout la pratique quotidienne qui permettra d'en corriger les défauts et de sélectionner les types les meilleurs et les plus utiles.

Des savants et des ingénieurs indiens ont mis au point une cuisine solaire pour une famille de trois à cinq personnes ; la fabrication de cette cuisine à des fins commerciales a déjà commencé, et l'usage en deviendra aussi répandu que celui des réchauds électriques dans les villes où le courant est peu coûteux. C'est là un excellent exemple de la liaison qui doit exister entre la recherche scientifique et les applications pratiques.

Dès maintenant, personne ne considère plus nos travaux comme des expériences physiques simplement curieuses. Néanmoins, dans les régions qui abondent jusqu'ici en ressources énergétiques d'autres catégories, certaines personnes parlent de l'inutilité de ces travaux. On peut résumer leur opinion en ces termes : "L'exploitation de sources d'énergie telles que le rayonnement solaire est très compliquée ; pourquoi s'en occuper alors que nous avons l'énergie vivante, que nous avons des combustibles ?"

C'est comme si l'on disait en voyant semer du blé : "Pourquoi faire un travail si compliqué alors qu'il est si simple d'acheter du pain chez le boulanger ?"

Nous devons intensifier nos efforts sur le plan théorique comme sur le plan pratique, en vue d'assurer l'exploitation de l'énergie solaire et de l'énergie éolienne. La large utilisation de ces sources d'énergie aura d'importantes conséquences sociales : il sera possible par exemple d'élever le niveau de vie d'une grande partie de la population mondiale, de fertiliser et de mettre en valeur les zones désertiques.

Nous pouvons et nous devons exploiter rationnellement les dons que nous prodigue le soleil. Nous devons intervenir activement dans les processus naturels de la transformation de l'énergie solaire, les adapter à nos besoins. C'est là une grande et noble tâche, bien digne de l'homme.

Le présent colloque a été utile, car il a permis d'échanger des observations et de préciser les points de vue communs. Nous adressons tous nos remerciements à nos hôtes pour l'excellente organisation de cette réunion.

Discours de

F. Trombe

Monsieur le président, Mesdames et Messieurs,

Au nom des délégués étrangers, je voudrais remercier les organisateurs de ce colloque. Nos remerciements iront tout d'abord au gouvernement de l'Inde dont l'accueil et la délicate hospitalité resteront dans notre souvenir. Il est prévu après ce colloque une grande excursion au-dessus du désert indien et nous aurons certainement encore dans cette seconde partie de notre séjour beaucoup d'occasions de nous réjouir de notre présence dans ce pays et de nous intéresser non seulement à son passé si prenant mais aussi aux multiples aspects de son activité présente.

Au D^r^ Bhatnagar et au D^r^ Krishnan s'adressent aussi nos vifs remerciements. New Delhi et le National Physical Laboratory ont tout fait pour créer à ce colloque international une ambiance de choix.

Je voudrais aussi exprimer notre reconnaissance aux délégués de l'Unesco, MM. Swarbrick, Ellis et Young, qui ont eu la lourde tâche de prévoir dans leurs moindres détails nos voyages, nos séjours et notre contribution scientifique. J'ai pu mieux que personne apprécier leur aimable bienveillance car, ne parlant que le français, j'ai dû bien souvent avoir recours à eux.

Dans une réunion internationale, les discussions directes sont les plus fructueuses : elles ont pu à New

Delhi se faire avec une grande facilité grâce à une excellente traduction immédiate des exposés de chacun ; j'exprimerai certainement le sentiment de tous en remerciant nos interprètes de l'effort qu'ils ont fait pour nous aider à nous comprendre.

Nous avons pu, au cours de ce colloque, entendre de nombreuses et intéressantes communications, aussi bien sur l'énergie éolienne que sur l'énergie solaire. Nous n'en sommes plus aujourd'hui aux petites expériences de physique amusante sur l'utilisation de ces formes d'énergie. Après avoir détruit une partie de ses forêts, l'homme a trouvé le charbon de terre, le pétrole, les chutes d'eau ; il songe maintenant que certaines de ces réserves énergétiques s'épuisent aussi et l'énergie nucléaire apparaît comme une possibilité de remplacement. Son règne sera durable et nous sommes de plus en plus nombreux à penser que d'autres formes d'énergie — celles dont il est question ici — l'accompagneront dans son essor. Et ce sont finalement notre bon vieux soleil et les phénomènes énergétiques qu'il provoque qui resteront les derniers dans la lice.

Addresses delivered at the final session of the symposium, 26 October 1954

Address by

A. V. BAUM

MR. CHAIRMAN, LADIES AND GENTLEMEN,

The interesting series of reports we have heard on the exploitation of perennial energy sources are added confirmation that the work done on them is useful and even essential. Experiment and close and trustworthy calculations provide evidence that in many instances the harnessing of these sources of power is even now both worth while and commercially viable. The development of practical units for the conversion of solar energy and wind power into other forms of energy and the formulation of plans for their introduction is imperative. It is also desirable that units be manufactured in quantity: the experience gained in daily use will do most towards the correction of faults and the selection of the soundest and most useful types.

Indian scientists and engineers have developed a solar cooking stove for families of three to five persons. It is already being manufactured on a commercial scale and is likely to become as common as electric hot plates in the towns where cheap current is available. It is an excellent example of the close "tie-up" that should exist between research and applied science.

We have reached a stage when no one any longer regards what we are doing as physical experimentation of merely academic interest. Nevertheless some persons, in areas well supplied so far with other sources of power, claim our work is pointless. They reason —more or less—that the harnessing of solar radiation and similar energy sources is extremely complicated and not worth bothering with when there is directly usable power to hand in the shape of fuel. That is about as sensible as asking why we bother with the complicated process of sowing and harvesting corn when it is so easy to buy bread from a baker.

Pure science and technology alike must redouble their efforts to harness the power of the sun and wind. The large-scale exploitation of these sources of energy will have important social repercussions in raising the living standards of much of the world's population and reclaiming the desert.

We can and must take advantage systematically of the gifts the sun showers on us. We must intervene actively in the natural processes which convert the energy of the sun into usable forms of energy and adjust them to our needs. The task is a great and noble challenge to mankind.

This symposium has been valuable because it has given us a chance to exchange experiences and find out what we agree on. We are all most grateful to our hosts for the excellent arrangements they made for this meeting.

Address by
F. TROMBE

MR. CHAIRMAN, LADIES AND GENTLEMEN,

On behalf of the foreign delegates, I wish to express our thanks to the organizers of this symposium and first and foremost to the Indian Government whose warm welcome and sedulous hospitality will long remain in our memories. When this symposium ends we are to be taken on an extensive tour over the Indian desert and this second part of our stay, too, will certainly afford us frequent occasions to be glad that we came to India and to take an interest not merely in the charm of her past but in her present activity in all its manifold aspects.

Our lively thanks are also due to Dr. Bhatnagar and Dr. Krishnan. New Delhi and the National Physical Laboratory have spared no pains to create ideal conditions for this international symposium.

I wish also to express our thanks to the Unesco representatives, Messrs. Swarbrick, Ellis and Young, who have had the heavy task of planning our travel, our accommodation and our scientific proceedings in every detail. I have, perhaps, been better placed than anyone else to appreciate their friendly goodwill as French is my only language and accordingly I have often had to turn to them for help.

In an international meeting, the best results come from direct discussion and at New Delhi this has been immensely aided by first-class simultaneous interpretation of each member's views; I feel that I speak for all in thanking our interpreters for what they have done to help us to understand each other.

In the course of this symposium we have listened to a great many most interesting papers both on solar energy and on wind power. Today our experiments on the use of these forms of energy are no longer on the miniature scale of amusing little conjuring tricks. Man had destroyed part of his forest heritage by the time he discovered coal, petroleum and water power. Now it is dawning on him that some of these latter power reserves are running out in their turn. Their likely successor—with a long run ahead of it—seems to be nuclear power and more and more of us are coming to think that its rise will be accompanied by that of other forms of energy—those we have been discussing here. In the final count, the last in the lists will be the enduring sun, and the forms of power which come direct from it.

Discursos pronunciados en la sesión de clausura del coloquio, el 26 de octubre de 1954

Discurso de
A. V. BAUM

SEÑOR PRESIDENTE, SEÑORAS Y SEÑORES:

Hemos escuchado la lectura de una serie de interesantes informes sobre la explotación de las fuentes permanentes de energía. Estos informes confirman una vez más la utilidad de esos trabajos e incluso su necesidad. Experimentos y cálculos exactos y dignos de fe muestran que, en muchos casos, esa explotación es desde el presente ventajosa y económica. Para ello es absolutamente necesario construir aparatos que permitan transformar la energía solar y la eólica en otras formas de energía y preparar planes para su utilización: es preciso iniciar la producción en serie de esos aparatos: la práctica diaria, sobre todo, permitirá corregir sus defectos y seleccionar los tipos mejores y más útiles.

Los hombres de ciencia y los ingenieros indios han construído una cocina solar para una familia de 3 a 5 personas; ha comenzado ya la fabricación en grandes números de esa cocina y su empleo se vulgarizará tanto como el de las cocinas eléctricas en las ciudades donde la corriente eléctrica es barata. Esto constituye un excelente ejemplo de la relación que debe existir entre la investigación científica y las aplicaciones prácticas.

Desde este momento, nadie considera nuestros tra-

bajos como experimentos físicos de mero valor teórico. No obstante, en las regiones que hasta ahora disponen de abundantes recursos energéticos de otras categorías, hay personas que hablan de la inutilidad de esos trabajos. Su opinión puede resumirse en esos términos: "La explotación de fuentes de energía como la irradiación solar es muy complicada; ¿por qué ocuparse de ello mientras dispongamos de energía viva, mientras tengamos combustibles?

Es como si viendo sembrar el trigo, dijéramos: "Por qué realizar un trabajo tan complicado cuando es tan fácil comprar el pan en la panadería?"

Es preciso intensificar nuestros esfuerzos tanto en el terreno teórico como en el práctico para poder explotar la energía solar y la eólica. La utilización en gran escala de esas fuentes de energía tendrá importantes consecuencias sociales: permitirá, por ejemplo, elevar el nivel de vida de una gran parte de la población del mundo, fertilizar y bonificar las zonas desérticas.

Podemos y debemos explotar racionalmente los dones que nos prodiga el sol. Debemos intervenir activamente en los procesos naturales de la transformación de la energía solar, adaptándolos a nuestras necesidades. Esa es una tarea grande y noble muy digna del hombre.

El presente coloquio ha sido útil porque ha permitido hacer un intercambio de observaciones y precisar puntos de vista comunes. Y, sobre todo, agradecemos a nuestros invitantes la excelente organización de esta reunión.

Discurso de

F. TROMBE

SEÑOR PRESIDENTE, SEÑORAS Y SEÑORES:

En nombre de los delegados extranjeros quisiera dar las gracias a los organizadores de este coloquio. Debemos agradecer sobre todo al gobierno de la India por la acogida que nos ha dispensado y su delicada hospitalidad quedará grabada para siempre en nuestro recuerdo. Para después del coloquio está prevista una gran excursión aérea sobre el desierto indio y, seguramente, tendremos en esta segunda parte de nuestra estancia muchas ocasiones de felicitarnos de nuestra presencia en este país y de interesarnos no sólo por su pasado tan notable, sino también por los múltiples aspectos de su actividad presente.

También debemos hacer participar de nuestro más vivo agradecimiento al Dr. Bhatnagar y al Dr. Krishnan. Nueva Delhi y el Laboratorio Nacional de Física han hecho todo lo posible para crear en este coloquio una atmósfera muy selecta.

También quisiera expresar nuestro reconocimiento a los delegados de la Unesco, Sres. Swarbrick, Ellis y Young, sobre quienes ha recaído la pesada tarea de preparar los más mínimos detalles de nuestros viajes, nuestra estancia en esta ciudad y nuestra contribución científica. Más que a nadie me ha sido dado a mí apreciar su amable benevolencia ya que, no hablando más que el francés, he tenido que recurrir a ellos con bastante frecuencia.

En una reunión internacional, los debates directos son los más fructíferos: en Nueva Delhi han podido celebrarse con gran facilidad gracias a una excelente interpretación inmediata de las manifestaciones de cada participante; estoy seguro de expresar el sentimiento de todos manifestando nuestro agradecimiento a los intérpretes por el esfuerzo por ellos realizado para que pudiéramos comprendernos.

En el curso del presente coloquio hemos tenido ocasión de escuchar numerosas e interesantes comunicaciones, tanto sobre la energía eólica que sobre la energía solar. Ya nos encontramos hoy en la fase de los pequeños experimentos de física recreativa sobre la utilización de esas formas de energía. El hombre, después de haber destruído una parte de sus bosques, encontró el carbón mineral, el petróleo, las caídas de agua; hoy teme que algunas de esas reservas energéticas también se agoten, y la energía nuclear aparece como una posibilidad para reemplazarlas. Su reino será duradero, pero somos cada vez más numerosos los que pensamos que otras formas de energía —aquéllas de que se trata aquí— la acompañarán en su desarrollo. Y es finalmente nuestro bueno y viejo sol y los fenómenos energéticos que provoca los últimos que quedarán en la palestra.

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